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Analysis of the structure of liners used for the modernisation of brick collectors

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Abstract: Brick sewers were designed as egg-shaped, pear-shaped, bell-shaped, vaulted, and even rectangular (sometimes with granite ceilings and floor slabs). In exceptional cases, circular sections were also made of brick. Efforts were made in order to ensure optimal flow conditions, and also that the cross-section was adapted to the shape of the rock mass pressure line. This is due to the fact that the most advantageous shapes for masonry collectors are shapes in which no tensile stresses will occur in any part of the cross-section under the influence of external loads. Nevertheless, sewage conduits degrade over time. The boundary conditions of their use also change, which affects the magnitude of mechanical and hydraulic loads. Further use of a sewer in such a case requires its renewal, and less frequently, modernization that results from the necessity to change its function. This is usually done by introducing a new conduit into the interior of the renovated or modernized sewer, which in literature is called a liner.

The aim of the analysis was to determine the thickness of the liners that strengthen the structures of brick channels with an inverted egg cross-section and with dimensions of 1050 x 700 mm, which are intended for gravitational sewage systems. The analysis included the performance of variant static and strength calculations for the assumption that the conduit after its modernization will be replaced with a conduit operating in the pressure system, which is a very rare requirement.

It was assumed that the best solution would be to use a CIPP (Cured In Place Pipe) liner.

Keywords: brick sewer; renovation; CIPP liner; modernization of brick sewers.

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1 Introduction

The first comprehensive sewage system project in Poland was developed in 1869 for Gdansk by the German engineer Wiebe. The implementation of this project was completely finished in 1871. The history of the development of the municipal sewage systems in Poland, however, should be associated primarily with Eng. William Lindley, the creator of the assumptions for the water supply and sewage system for Warsaw, and also his son Sir William Heerlein Lindley, who executed the project. The works of Sir William Heerlein Lindley carried out in Poland include projects and their implementation, as well as opinions concerning the sewage system and water supply for the cities of Lodz (1907–1909), Lviv (1909), Radom (1912) and Wloclawek (1910–1914) [3,4]. A similar development of sewage networks has also taken place in the western parts of present-day Poland (e.g. in Wroclaw). In turn, the history of the development of the sewage systems in the areas of the former Austrian partition is somewhat different. The cross sections of brick channels were designed as egg shaped, pear shaped, bell shaped, vaulted and even rectangular (sometimes with granite floor slabs). In exceptional cases, circular sections were made of brick. However, in most cases, efforts were made to ensure that the cross-sectional shape allows for optimal flow conditions, and also that it is adapted to the shape of the rock mass pressure line. This is due to the fact that the most advantageous shapes for brick collectors are those in which no tensile stresses occur in any part of the cross section under the influence of external loads. Nevertheless, the structures of sewers degrade over time. The boundary conditions of their use also change, which affects the magnitude of mechanical and hydraulic loads. Leaving a sewer for further use in such a case requires its renewal, or less frequently, modernisation, which results from the necessity to change its function. This is usually done by the introduction of a panel into the interior of the renovated or modernised sewer, which in literature is called a '*liner*'.

The aim of the analysis was to determine the thickness of liners intended to strengthen the structure of a brick sewer that has an inverted egg cross section and dimensions of 1050 × 700 mm, and which function in the gravity sewage drainage system. The analysis included the performance of variant static and strength calculations in order to assume that the conduit in question, after modernisation, will be replaced with a conduit operating in the pressure system, which is a very rare requirement.

It was assumed that the best solution would be to use the so-called *liner* 'sleeve', referred to in literature as a *Cured In Place Pipe* (CIPP).

2 Multilayer shell structures (sleeves)

Sleeves are one of the most frequently used types of liners that are applied in trenchless technologies for the renovation and reconstruction of network infrastructure conduits. The idea of this technology is to introduce a liner inside the conduit in the form of a sleeve that is later hardened in place. Depending on the condition of the renovated sewer's structure, it can be renovated (only sealed) or reconstructed (its load-bearing capacity increased, or a self-supporting sleeve introduced).

The basic materials for the production of sleeves intended for the trenchless renewal of conduits are polymer composites made of either polyester or glass fibres with organic resins. The most commonly used resins are polyester, epoxy or vinyl ester. Renewed conduits must first be cleaned and subjected to (at least) a CCTV inspection. There are one-stage (more commonly used) and two-stage technologies. The sequence of actions (preceded by investigations of the conduit's condition) within the one-stage technology is as follows:

- opening of subsequent inspection chambers;
- closing the section of the conduit, for example, with pneumatic plugs;
- disconnecting connections;
- cleaning the conduit;
- a visual inspection (using a camera [CCTV] or direct);
- inserting a sleeve (liner) using hydrostatic pressure, compressed steam or compressed air;
- thermal, or with the use of ultraviolet (UV) rays, hardening of the resin;
- a pressure test;
- opening of connections and
- putting the repaired section of the sewer into operation.

The shape of the cross section of the sleeve should correspond to the circumference of the cross section of the damaged conduit. However, this is not always possible, for example, when the thickness of the sleeve is large or the cross section of the conduit is deformed. In such cases, the sleeve may not fit tightly against the inner surface of the conduit, or may locally wrinkle. Both situations are very unfavourable, as most geometric imperfections significantly reduce the load capacity of the sleeve [5].

In the case of thermosetting sleeves, hardening of the resin is accelerated by heating the water that fills the liner, or by supplying hot steam. The curing time depends on the external temperature, the type of sleeve and the dimensions of the renovated sewer. During the entire process, hydrostatic pressure or vapour pressure is maintained inside the liner. This pressure initially allows the liner to be introduced using the inversion method and then pressed against the inner surface of the conduit.

There are also known technologies in which polymer–glass composites and specially modified resins hardened using UV rays are used to make the sleeves. Such sleeves are often referred to as *UV-Liners*. The technology involves the introduction of a sleeve, which is made of glass fabric that is saturated with resin, into the cleaned section of the conduit, filling it with compressed air and curing it with a set of lamps emitting UV radiation.

In two-stage technologies, before the introduction of the basic sleeve, the so-called *preliner* (i.e. a thin sleeve that protects against uncontrolled outflow of resin in the case of cracks and cavities in the sewer's walls) is implemented in stage I. Such uncontrolled outflow of the resin is dangerous for both the environment and for the sleeve because it weakens its structure. For these reasons, the solution with the use of a *preliner* is very advantageous, especially in the case of conduits with numerous leaks.

With the use of sleeves, sections of conduits with a length not exceeding 200 m (depending on the diameter) are most often renewed. After making the liner, the connections can be opened in a trenchless manner by milling holes with the use of special robots.

By using sleeves, it is possible to successfully renew conduits not only with a non-circular cross section, but also with deformed cross sections (with so-called geometric imperfections), which is a great advantage. This is due to the fact that the stiffness of the resin-saturated sleeve during insertion into the damaged conduit is negligible, and the sleeve only reaches the assumed strength parameters after its hardening. As a result, the uncured sleeve, when subjected to internal pressure during installation, adheres precisely to the internal surface of the sewage pipe being renovated, even if (which happens often) the conduit is deformed to some extent. However, it should be taken into account that as a result of the deviation from the designed and calculated shape of the cross section of the sleeve, it loses part of its load-bearing capacity. This should be considered in the static and strength calculations, on the basis of which the thickness of the sleeve is selected.

In practice, there are no differences regarding the technology or used apparatus when introducing sleeves into conduits with cross sections that are not circular: for example, egg shaped, pear shaped and others. In every case, regardless of the shape of the cross section, it is necessary to adapt the circumference of the sleeve to the circumference of the cross section of the conduit. Moreover, appropriate static and strength calculations should be performed in each case.

The renovation of conduits with the use of sleeves is usually cheaper than building new sewers. Unfortunately, in many cases, these important decisions are not made rationally on the basis of in-depth technical analyses carried out by independent entities, but only on the basis of intuition and trust in companies that distribute sleeve technologies. This causes many errors. The use of sleeves that are too thin, and thus cheaper (which is often proposed by suppliers), may lead to their deformation due to external loads, whereas the use of sleeves that are too thick may cause an unjustified increase in investment costs. Prior to organising a tender for such investments, it is necessary to prepare a design based on appropriate standards or guidelines, while at the same time taking into account the technical condition of the existing conduit and all the operating loads.

Particular attention should be paid to static and strength calculations. This is facilitated due to the possibility of using the German ATV-DVWK-M-A127P guidelines, which were published in 2000 [1] (with their newer version DWA-A 143-2), and their supplement – the ATV-DVWK-A127P guidelines [2]. These guidelines are devoted to the designing of liners. Calculation of the structure of a liner, while taking into account the geometric imperfections of the conduit, is extremely difficult and requires the use of special calculation algorithms based on the Finite Element Method (FEM), such as the algorithm developed at Wroclaw University of Science and Technology [5].

3 Static and strength analysis

3.1 Assumptions adopted for the analysis

In the analysed case, static and strength calculations were made on the basis of the German ATV-DVWK-M-A127P and ATV-DVWK-A127P guidelines [1,2], which are commonly used in Poland and in many European countries. According to DIN EN 725-5, the methods of technical rehabilitation of underground sewage pipes can be divided into the following groups: repair, renovation and refurbishment. In the analysed case, due to the change in the functioning mechanism of the conduit from the gravity system to the pressure system, modernisation of its structure should be considered.

The guidelines, on the basis of which the structure analysis was carried out, take into account two possibilities: relining and assembly methods that can be used in the renovation of sewers. The relining method, which is the subject of the analysis, involves the introduction of a self-supporting liner into an old conduit. Such a liner can either adhere closely to the inner surface of the sewer (‘*close-fit*’ or ‘*rib-lock*’ technologies) or can be in the form of elements that are freely inserted into the conduit (with a cross section that matches the cross section of the renovated/modernised structure of the conduit), which after being connected constitutes a self-supporting liner. The space between the conduit and the liner is filled with an appropriate injection material.

Correctly conducted static and strength calculations of the liner should consider the following:

- imperfections that characterise the conditions of placing the liner,
- checking the stresses under long-term hydrostatic pressure of groundwater,
- issues concerning contact stresses and
- the need to perform non-linear calculations (second-order theory).

The last condition results from the simultaneous occurrence of low values of the modulus of elasticity *E*, high axial forces and the relatively small thickness of the liner’s wall. These specific calculation elements are included in guidelines [1]. The principles concerning the dimensioning of liners that are set out in the guidelines apply to the execution state and to the operation state of the renovated conduit. However, they do not take into account all the boundary conditions that may occur in practice. According to the guidelines, for special cases, such as liners with non-circular sections, discrete changes in the value of the elastic modulus *E* and the thickness of the liner’s wall, the use of a liner only on certain sections of the conduits, etc., the analysis should be carried out based on a scientifically justified calculation methodology.

In order to perform standard static and strength calculations, it is necessary to have information regarding soil and water conditions and the parameters of the construction material of the conduit and its wall thickness, as well as the results of investigations that illustrate the damage to the conduit. This allows the current technical condition of the building structure to be determined, which, in accordance with the guidelines, can be classified into one of the following;

– **I technical condition:** The conduit has retained its load-bearing capacity. There can be minor damage, for example, in the form of leaky joints or hairline scratches in its walls.
– **II technical condition:** The existing system (the conduit–soil medium) has retained its load-bearing capacity. Permissible for this state of damage are longitudinal cracks and slight deformations of the cross section in the conditions of soil resistance in the side zones of the conduit, which are confirmed by, for example, long-term observations.
– **III technical condition:** The existing system (the conduit–soil medium) has lost the ability to independently transfer loads; significant deformations of the cross section can be found. Contrary to the conduit in the I and II technical conditions, the designed liner will have to be involved in the transmission of loads.

According to the guidelines, the following load cases can be considered for a conduit in the I and II technical conditions:

– external water pressure acting on the liner;
– internal pressure (negative pressure, overpressure with a value determined by the height of the terrain above the bottom of the sewer in the considered place);
– self-weight;
– influence of temperature (cooling, heating) and
– technological stresses related to a specific renewal/modernisation technology.

Any special values of loads that were caused by the external pressure of water in the event of damming or flooding should be taken into account on the basis of individual calculations that are adequate for the situation. In such cases, the verifying calculations can be performed as specified for short-term loads. In order to ensure a sufficient circumferential stiffness of the liner, regardless of the groundwater level, an equivalent pressure of no less than 0.15 bar should be assumed. In such cases, the verifying calculations should be performed as specified for long-term loads. In order to simplify the calculations, the three-dimensional structure (shell) can be reduced to two dimensions (plane state of deformations, shield). A further facilitation is the possibility of considering the liner as a rod system, which is well supported on the inner surface of the existing sewage conduit. When using liners with E_D < 10,000 MPa, elastic supports should be used instead of rigid supports. Depending on the way of supporting the liner in the existing conduit, and with the inevitable occurrence of initial deformations and a possible annular gap, external loads lead to the occurrence of large axial forces N and bending moments M. It is then required to apply the second-order theory in the calculations (taking into account the deformations in the appropriate equations) and to iteratively determine the size of the contact zones.

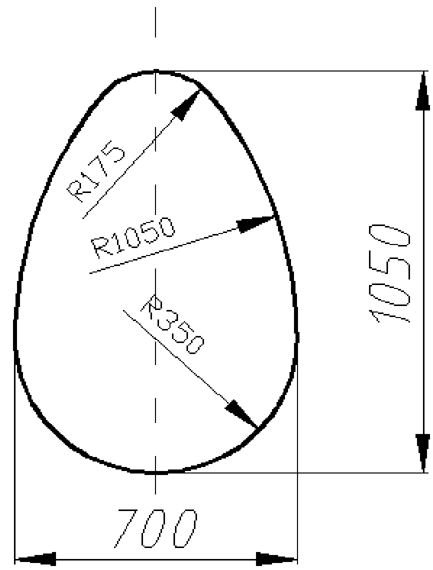

Figure 1: Internal dimensions (in mm) of the conduit's cross section.

3.2 The input data

On the basis of a CCTV camera inspection, as well as a macroscopic examination, it was found that the conduit is in the second technical condition according to the ATV criteria, that is, it has not lost the ability to carry external loads (soil pressure, backfill loads). Moreover, it was assumed that the condition of the conduit is stable and has not changed over a long period of time. Data concerning its soil and water conditions were obtained from the ordering party. The shape of the cross section of the structure, as well as its dimensions are shown in Figure 1.

The static and strength calculations were made using the finite element method and COSMOS/M v 2.5 software, while assuming the following output data:

- conduit made of brick and cement mortar, with its internal dimensions of the cross section as shown in Figure 1;
- inverted egg-shaped sleeve with dimensions of 700 mm (width) × 1050 mm (height);
- thickness of the conduit's wall equal to 25 cm;
- groundwater level 1.50 m above the bottom of the sewer;
- internal operating pressure equal to 0.46 bar;
- pressure during the tightness test equal to 1.0 bar;
- no scratches on the existing structure;
- no local deformations (faults) and
- the size of the annular gap was adopted at the minimum level in accordance with the ATV guidelines [1].

In order to find a rational solution, the analysis covered two types of liners:
- type I – sleeve made of felt fabric (polyester fibres) and
- type II – multi-layer sleeve.

3.3 Liner made of polyester fabric (type I)

The analysis covered two load schemes:
- Scheme 1 – load of hydrostatic pressure from a 1.50-m-high water column (considered from the bottom of the conduit [empty conduit]) and
- Scheme 2 – load with an internal operating pressure of 0.46 bar (46 kPa). When checking the load-bearing capacity condition, the partial safety factor $g = 2$ was taken into account.

When adopting the calculation model, the fact that the cross section of the sleeve with respect to its vertical axis is symmetrical was taken into account, and therefore, half of the structure on a 1-m-long fragment was considered. The scheme of dividing the model into finite elements is shown in Figure 2.

Plate finite elements with four nodes and six degrees of freedom in a node were used to make the model. Taking into account the support conditions, the final model consisted of 690 elements with 770 nodes and 2277 degrees of freedom. The following strength parameters of the liner were adopted for the calculations:
- short-term Young's modulus $E_R = 3000$ MPa and long-term Young's modulus $E_L = 1500$ MPa,
- Poisson's ratio $n = 0.3$ and
- tensile strength $s_{bZ} = 25.0$ MPa.

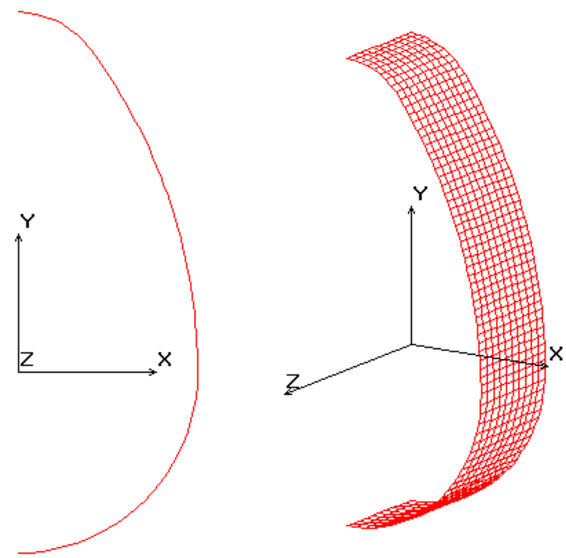

Figure 2: Calculation scheme of the finite element method.

Table 1: Thicknesses of the sleeve calculated for the assumed load cases.

Liner thickness		Scheme 1		Scheme 2	
19 mm[a]	Max deformations (mm)	32.2	Yes		
	Max stresses (MPa)	5.4	Yes	56.4	No
40 mm	Max deformations (mm)				
	Max stresses (MPa)			12.9	No
41 mm[b]	Max deformations (mm)	3.2	Yes		
	Max stresses (MPa)	1.23	Yes	12.29	Yes

[a]The smallest wall thickness for which the load-bearing and service-life conditions are met when considering scheme 1. [b]The smallest wall thickness for which the load-bearing capacity condition is met when considering scheme 2.

The analysis was performed for three load schemes:

Scheme 1 – loads involving the hydrostatic groundwater pressure (the level of groundwater of 1.5 m above the conduit's bottom). For this assumption:
- the load-bearing capacity condition is met if the normal stresses are less than $s_{bZ}/g = 25/2 = 12.5$ MPa and
- the condition of serviceability is met if:
  - horizontal deformation does not exceed 10% of the maximum horizontal dimension of the cross section; in this case, 70 mm and
  - vertical deformation does not exceed half of the horizontal deformation value; in this case, 35 mm.

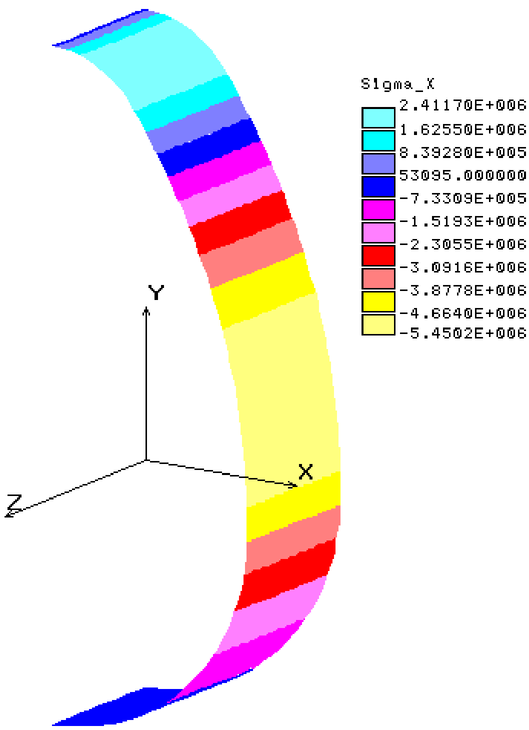

Figure 3: Normal stresses (load scheme 1 – wall thickness equal to 19 mm).

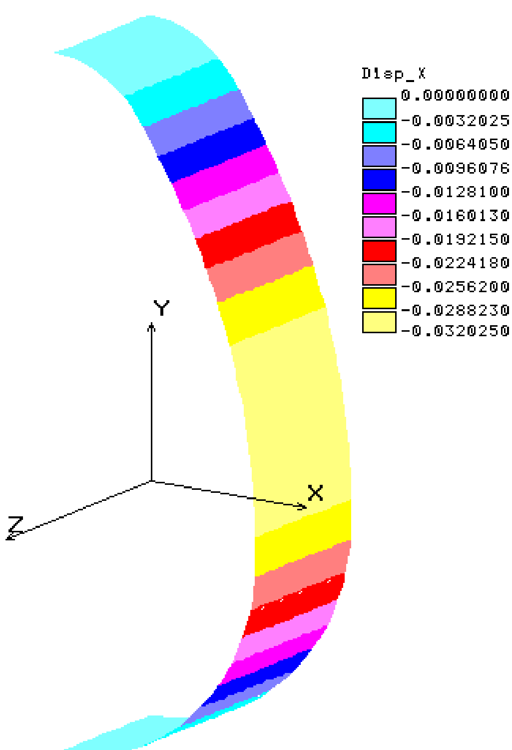

Figure 4: Horizontal displacements (load scheme 1 – wall thickness equal to 19 mm).

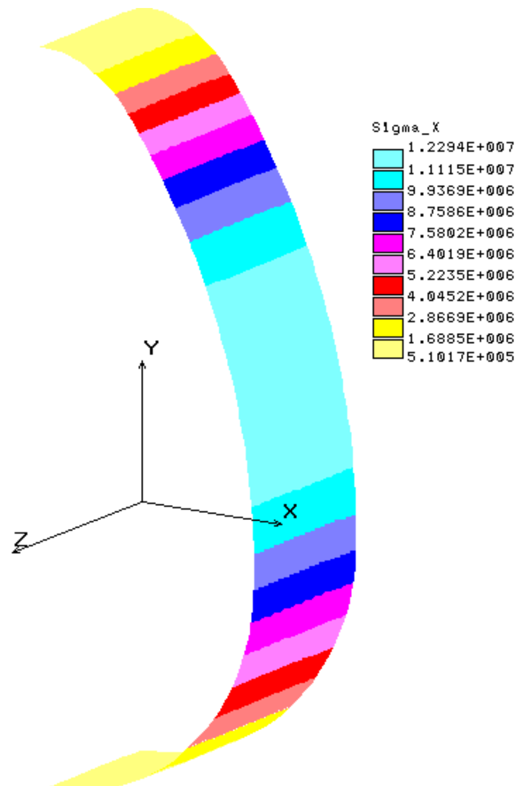

Figure 5: Normal stresses (load scheme 2 – wall thickness equal to 41 mm)

Scheme 2 – loads involving an operating internal pressure of 0.46 bar. For this assumption:

– the load-bearing capacity condition is met (with the adopted safety factor equal to 2.0) if the normal stresses are less than $s_{bz}/g = 25/2 = 12.5$ MPa.

The results of the calculations are presented in Table 1, whereas Figures 3–6 present the calculated sample values of the stresses and displacements.

As can be seen from the presented calculations, a sleeve with a thickness of 19 mm should be used for the safe transfer of external loads (from groundwater pressure). However, for the safe transfer of internal loads (internal operating pressure), a 41-mm-thick sleeve should be used. In addition, the adopted sleeve should be tested regarding its tightness in accordance with the procedures adopted in the design documentation – by loading it with an internal pressure of 1.0 bar, which will result in the need to increase its thickness. Due to the shape of the cross section of the conduit and the sleeve (inverted egg), a tight fit of such a thick liner, especially in its key zone, will be difficult. Therefore, it has been found to be more advantageous to use a sleeve with a higher modulus of elasticity (polymeric), and hence with a lower thickness.

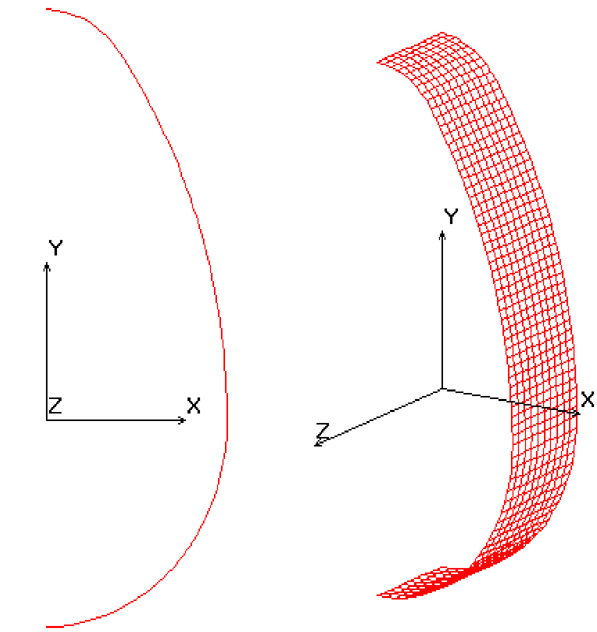

Figure 6: Calculation scheme of the finite element method.

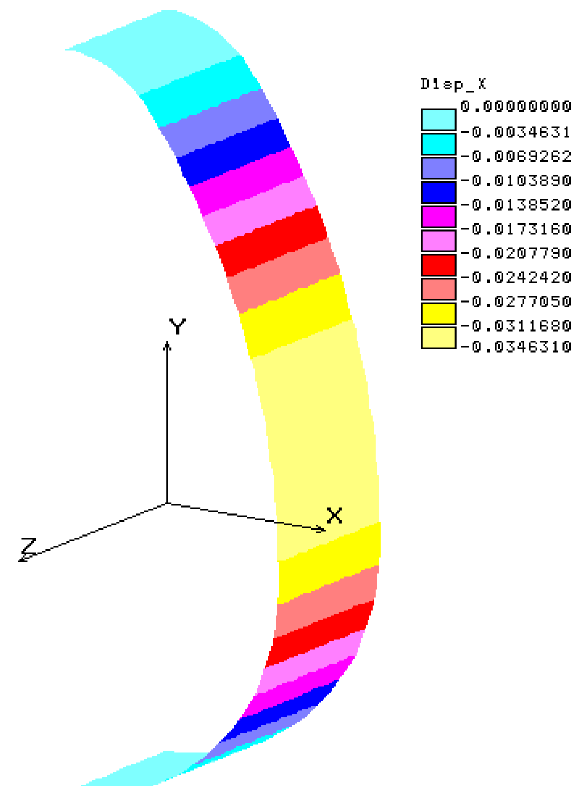

Figure 8: Diagram of horizontal displacements, wall thickness equal to 12 mm, load scheme 1.

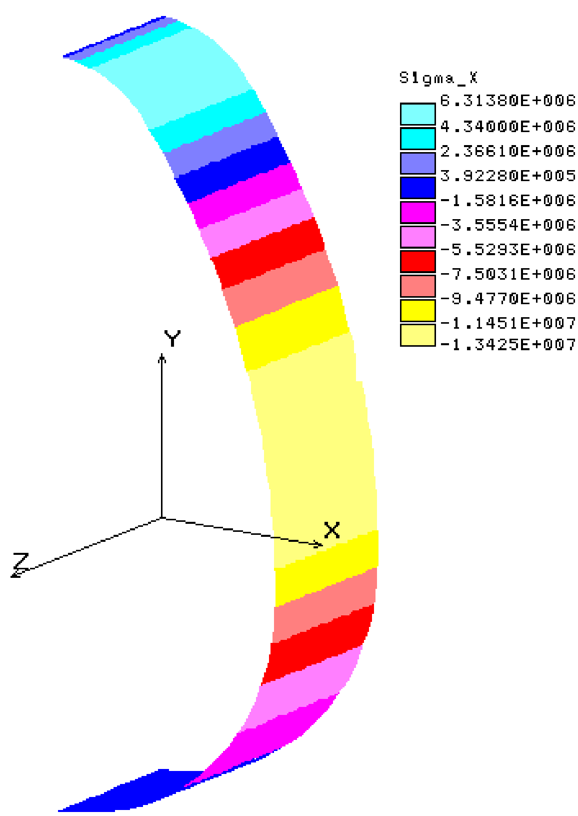

Figure 7: Diagram of normal stresses, wall thickness equal to 12 mm, load scheme 1.

3.4 Static and strength calculations of the polymer liner

In this case, the renewal of the sewer was designed with the use of a *Mazur Liner I* sleeve with Young's modulus E_L = 5500 MPa and Poisson's ratio n = 0.3. The value of Young's modulus was assumed on the basis of the test results of samples that were taken from the pilot installation of such a sleeve in a masonry sewer in Wroclaw. The research was carried out at Wroclaw University of Science and Technology. On its basis, the average value of the short-term modulus E_R = 11,052 MPa was determined. It is assumed that the value of long-term modulus E_L is no less than 0.5 E_R. The long-term tensile strength when bending was assumed to be s_{bZ} = 300 MPa based on the results of the research carried out at the Institut fur Unterirdische Infrastruktur in Germany (with which the authors have been cooperating for many years). Two load schemes were considered:

– Scheme 1 – loads involving the hydrostatic groundwater pressure (the level of groundwater 1.5 m above the conduit's bottom) and

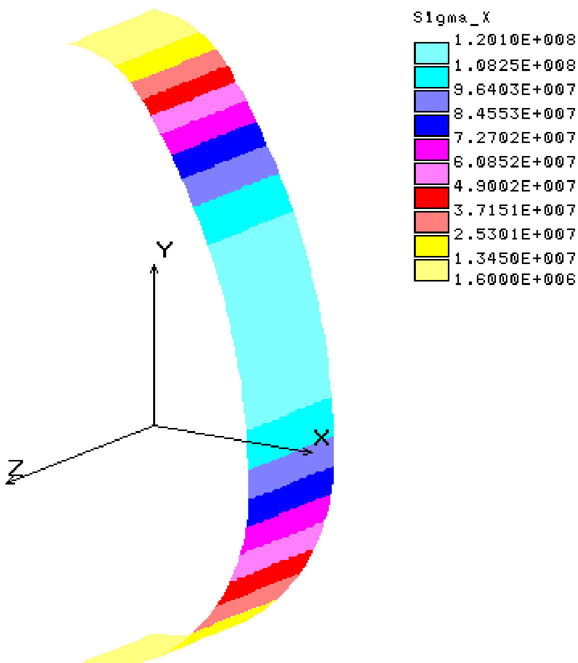

Figure 9: Diagram of normal stresses, wall thickness equal to 13 mm, load scheme 2.

– Scheme 2 – loads involving an internal pressure of 0.46 bar (46 kPa) – operating pressure; when checking the load-bearing condition, the partial safety factor g = 2.0 was taken into account while assuming that the sleeve transfers external loads without cooperating with the old conduit.

The scheme of the division into finite elements is shown in Figure 6 (a fragment of the sleeve with a unit length was considered).

Plate finite elements with four nodes and six degrees of freedom in a node were used to create the model. Due to its symmetry, half of the structure was considered. Taking into account the support conditions, the final model consisted of 690 elements with 770 nodes and 2277 degrees of freedom. The calculations were performed for two load schemes:

– Scheme 1 – groundwater pressure

As a result of the conducted calculations, a wall thickness of 12 mm was obtained, at which the maximum horizontal displacement is equal to 34.6 mm, the horizontal narrowing of the cross section is 2 ´ 34.6/700 ´ 100% = 9.9% < 10%, the maximum vertical displacement is 57.4 mm, the vertical narrowing of the cross section is 2 ´ 57.4/1050 ´ 100% = 5.5% < 10% and the maximum normal stresses s_1 = 13.4 MPa < s_{bz}/g = 300/2 = 150 MPa. The normal stresses are shown in Figure 7, and the displacements are presented in Figure 8.

A 12-mm-thick sleeve meets all the static and strength criteria with regards to external loads (groundwater).

– Scheme 2 – operating internal pressure

The tensile stresses in the wall of a 12-mm-thick sleeve subjected to an operating pressure of 0.46 bar were verified. As a result of these calculations, the value of normal stresses of s_1 = 176.3 MPa > s_{bz}/g = 300/2 = 150 MPa and the real safety factor g = 1.7 < 2.0 (required safety factor) were obtained.

Therefore, analogous calculations were carried out while assuming the thickness of the sleeve of 13 mm. As a result of these calculations, the tensile stresses in the sleeve wall of s_1 = 120.1 MPa < s_{bz}/g = 300/2 = 150 MPa and the real safety factor g = 2.5 > 2.0 (required safety factor) were obtained. The normal stresses are shown in Figure 9.

4 Summary

As can be seen from the conducted analysis regarding the determination of the thickness of a sleeve, finding cheaper solutions (felt fabric), which are made of a material with a lower Young's modulus, due to assembly reasons may turn out to be disadvantageous in conduits with a complex cross-sectional shape.

In the case of the examined conduit (inverted egg), a tight fit of a thick sleeve, especially in the key zone, would be very difficult. Therefore, an analysis was carried out in order to use a sleeve with a high modulus of elasticity (polymeric) and a smaller thickness.

The conducted calculations showed that changing the material allowed for a reduction of the thickness of the sleeve from 41 to 13 mm, which enabled the liner to be adapted to the shape of the sewer's cross section. For additional reinforcement of the renovated structure, any empty space between the sleeve and the wall of the old conduit can be filled with grout.

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