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Rigidity of Flanged Joints in Prefabricated Tunnel Linings with Tensile Bonding

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ABSTRACT

The article considers the issue of estimating rigidity of the longitudinal flange joint of prefabricated tunnel linings with tensile bonding. Rigidity of flange joints affects correctness of estimation of predicted forces in tunnel linings. The tunnel design standards indicate the need to consider rigidity of joints of segments of prefabricated tunnel linings when calculating the forces in the load-carrying structures, however, the question of estimating the magnitude of the rigidity and methods for accounting for it remains open.

The objective of the research is to study design assumptions and to reveal some results of estimation of rigidity of ordinary bolted joints of segments of prefabricated tunnel linings, as well as the effect of the rigidity on the forces in tunnel linings. The issue is relevant when performing checking calculations of existing structures and when designing new linings with rigid bolted joints and other tensile bonding elements.

The article provides an analytical solution of the problem based on the compatibility of deformations of prefabricated elements, and shows the dependences obtained of the angle of mutual rotation of rigid segments of tunnel lining on bending moments, longitudinal forces, and geometric dimensions of lining elements. The correctness of the conclusions was verified by a series of numerical experiments resulted in building of refined curves of the dependences of the same parameters, and in estimation of the spatial operation of cast-iron tubing in the contact area.

Solving the contact and physically nonlinear problem of operation of a flange joint of cast-iron tubing with tensile bonding has allowed to identify at the beginning a set of linear deformations of functions of the dependence of the angle of rotation of the segments on the forces acting in them for a specific configuration of elements. A technique for applying the research results for modelling tunnel linings as a plane problem in the GTS NX environment is disclosed. Comparative modelling of the same type of test tasks for operation of annular tunnel linings showed that under various soil conditions, with introduction of joint rigidity parameters, an increase in bending moments up to 8 % is observed in the linings while longitudinal forces remain practically unchanged.

Keywords: *transport, tunnels, tensile bonding, rigidity of joints, moment of a force in joint, lining modelling, inelastic behaviour.*

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The text of the article in Russian is published in the first part of the issue.
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INTRODUCTION

Features of modelling the operation of cast-iron linings with tensile bonding between tubing suppose considering the location and size of initial gaps in joints and the compliance of joints. This circumstance is considered in the requirements of clause 5.6.5 of SP 122.13330.2012[1], concerning calculations of structures for the so-called first group of limit states. The values of joint compliance are usually determined by the so-called joint moments, upon reaching which the stiffness of the joint passes into the plastic stage [1–3]. However, the scientific literature on the design and calculation of tunnels [4; 5], does not clearly indicate what the rigidity of a standard flanged bolted joint should be before the transition of the joint into a plastic hinge and what dependencies are characteristic of this rigidity. At the same time, modern tunnel design methods have plenty of opportunities to clarify the nature of operation of cast iron tubing and other tunnel linings with tensile bonding in flange joints. The topic is especially relevant when performing checking calculations of existing tunnel linings.

A significant amount of research on the effect of joint rigidity by numerical methods has been carried out in [6; 7], that contain comparative calculations of forces in prefabricated tunnel linings depending on the obtained rigidity coefficients. As rigidity coefficients, the authors understand the ratio of deformative properties of joints of lining segments with a specified rigidity to deformative properties of the segments of prefabricated linings themselves. These works note a change in the forces in prefabricated, however, they recommend considering the rigidity rates as constant, regardless of the forces in the elements. The authors of [8; 9] studied also estimates of the rigidity of flanged joints under rock pressure and seismic effects.

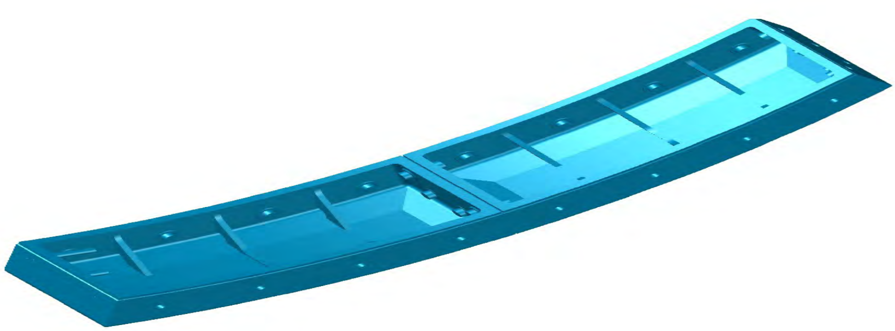
The *objective* of the research is to study design assumptions and reveal some results of estimation of rigidity of ordinary bolted connections of segments of prefabricated tunnel linings, as well as the effect of the rigidity on the forces in tunnel linings. The research has been based on analytical and experimental *methods* and computer modelling.

RESULTS

Tubing is cast product made of grey cast iron (gray iron) with a «back», four sides and stiffeners (stiffening ribs). Sections of tubing are connected to each other in the direction transverse to the axis of the tunnel, as a rule, by four bolts made of ordinary steel with a diameter of 20–45 mm. The cross-connection of two tubing sections is shown in Pic. 1. The paper considers the node of the flange (transverse) connection, although the design of tubing linings also provides for longitudinal connection of the rings to each other (horizontal bracing). Horizontal bracing can also be involved in operation of load-bearing structures, but subject to significant deformations of the linings, which turn the load-bearing structures into a pipe lying on an elastic foundation [10; 11].

Static calculations of linings, which consist in estimating the force acting in load-bearing structures of lining, are carried out using the methods of structural mechanics and continuum mechanics [12; 13]. The calculation methods described in the literature are based on considering operation of the lining both in the elastic stage and regarding linear rigidity of the flange joints [14; 15]. In fact, the connection of elements is

[1] SP [Code of Rules] 122.13330.2012 Railway and road tunnels. Updated version of SNiP [Construction standards and rules] 32-04-97 (with Amendments No. 1, 2).



Pic. 1. 3D model of the transverse joint of cast-iron tubing [developed by the authors].

neither absolutely rigid nor linearly elastic, especially in the absence of bracing of longitudinal joints or in case of small longitudinal deformations. In this situation, due to the deflection of the end walls and elongation of the bolt connections, the joints between the tubing sections open.

For the first group of limit states, the limit values of the forces N_b are determined through the standard resistance of the bolted steel R_b, n, taking into account the uniformity coefficient k [16]:

$$N_b = A_b \bullet R_b, n / k. \quad (1)$$

When the joint is opened from the inside, a collapse zone is formed at the rounding of the end of the tubing, through which the normal force N and the force in the bolts N_b of the most stressed inner row are transmitted. The height of the collapse zone is:

$$x = \frac{N + N_b}{bR_p}, \quad (2)$$

where x is the height of the collapse zone;

b – the width of a lining element;

R_p – design strength of the lining material.

Moment in plastic hinge:

$$M_{st}^{+} = N\left(a_1 - \frac{x}{2}\right) + N_b\left(a_2 - \frac{x}{2}\right), \quad (3)$$

where $a_{1,2}$ – the distance from the point of mutual rotation to the row of bolts shown in Pic. 2.

As a result, there is a redistribution of forces in the lining with an increase in its bearing capacity. The limit state regarding the opening of the joints occurs much earlier than the limit state of the strength of the joints.

If the moment at the joint is $M \le M_{st}^{+}/b$, then the calculation is performed for the elastic stage, and if $M > M_{st}^{+}/b$ then a plastic hinge emerges. The elastic behaviour is implied dictated not by the bending rigidity of the tubing, but by the rigidity of the bolted joint at the joint of the tubing.

In the case of the action of negative moments, the collapse zone is formed at the groove, that is, on the most compliant end surface of the tubing. When calculating the height of the collapse zone, it is not the full width that is entered, but the sum of sufficiently rigid sections through which the force is transmitted:

$$b_0 = 2 \bullet (b_k + \delta), \quad (4)$$

where b_k is annular rib thickness;

δ – end wall thickness.

The force per one bolt of the inner row:

$$N_b^n = \frac{1}{m_1} \bullet \frac{M - N(a_N - r)}{(a_1 - r)^2 + (a_2 - r)^2} \bullet (a_1 - r), \quad (5)$$

where r – rounding radius on the face of the lining element.

The solution of equations (1)–(5), based on the analysis of the limit state, are given in the literature on the design of tunnels [2; 16].

To determine rigidity of a bolted joint, let us consider the deformation scheme of the joint of a cast-iron tubing, shown in Pic. 2. The sum of the moments of the forces acting at the joint when turning around the point O or around the points located along the radius of the edge of the tubing, allows drawing up an equation for the balance of forces:

$$M = N \bullet a_N + (N_1 \bullet a_1 + N_2 \bullet a_2). \quad (6)$$

When the joint opens under the action of forces, each bolt (a pair of bolts located in the same row) will receive an increment in length δ, which can be associated with the angle of rotation α, expressed in radians, by the dependencies:

$$\delta_{1,2} = \alpha \bullet a_{1,2}. \quad (7)$$

Hooke's law, which determines the classical dependencies of the relative deformations of bolts ε with tensile forces in them is:

$$N_{1,2} = \varepsilon_{1,2} \bullet E_{bs} \bullet A_{b1,2}, \quad (8)$$

where E_{bs} – modulus of elasticity of steel of which bolts are made;

$A_{b1,2}$ – total area of bolts located in one row.

From the definition of relative strain and according to Pic. 2 it follows that:

$$\varepsilon = \frac{\delta_{1,2}}{l_b}. \quad (9)$$

Substituting (7)–(9) into (6), one can obtain the equation for the dependence of the bending moment at the joint and the angle of rotation of the joint around the edge of the tubing:

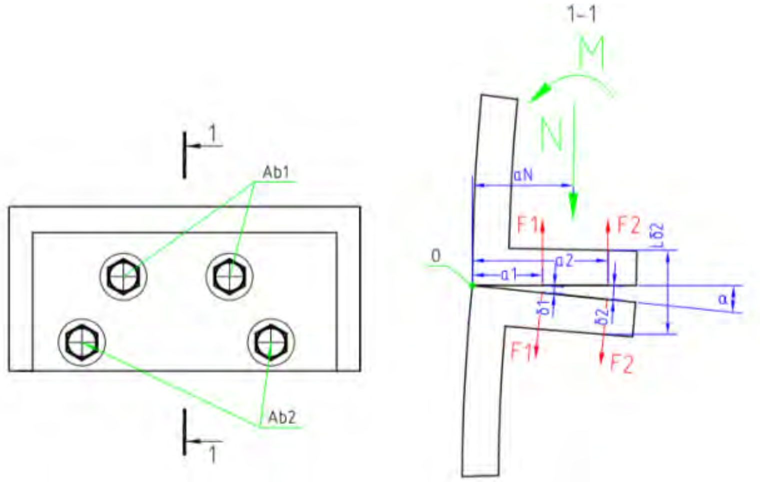
$$M = Na_N + \frac{E_{bs}}{l_b}\alpha\left(A_{b1}a_1^2 + A_{b2}a_2^2\right). \quad (10)$$

If the areas of all four bolts in the joint are the same and equal to A_b, then equation (10) can be rewritten as:

$$M = N \bullet aN + k \bullet \alpha, \quad (11)$$

where $k = 4A_b \frac{E_{bs}}{l_b}\left(a_1^2 + a_2^2\right)$ is coefficient of linear rigidity of the joint.

Given the limiting values of relative deformations, it is possible to determine the limiting angle of rotation of the joint. The moment of the limit state in terms of the angle of rotation during the formation of a plastic hinge will be the moment when the deformation in the



Pic. 2. Joint deformation scheme [developed by the authors].

bolt (row of bolts) farthest from the pivot point ε_2 reaches the limit ε_{lim}:

$$\alpha_{\lim} = \varepsilon_{\lim}\frac{l_{b2}}{a_2}, \qquad (12)$$

and the angle of rotation itself will linearly depend on the forces acting at the joint and the geometry of the connection, until in one of the rows of bolts their material passes into the plastic stage:

$$\alpha = \frac{M - Na_N}{k}. \qquad (13)$$

Linear dependence (11) is maintained until the bending moment reaches the moment of transition to the initial plastic stage $M \to M'$, with the angle of rotation $\alpha \to \alpha'$. In equation (10), the relative deformation of the bolt farthest from the turning point ε_1 transforms into a yield plastic zone $\varepsilon \to \varepsilon_T$. In this case, it is assumed that the material of the bolts acts as an elastic-plastic material according to the bilinear Prandtl diagram. The moment of transition is defined as:

$$M' = N \cdot a_N + \frac{E_{bs}}{a_2} \cdot \varepsilon_T \left(A_{b1} \cdot a_1^2 + A_{b2} \cdot a_2^2\right), \qquad (14)$$

and the angle will be equal to:

$$\alpha' = \frac{l_b}{a_2}\varepsilon_T, \qquad (15)$$

With a further increase in the moment $M > M'$, the stress in the bolts of the far row does not change, and the overall rigidity of the bolted connection decreases:

$$M = N \cdot a_N + \alpha \cdot k' + m_{yield}, \qquad (16)$$

where $k' = \frac{E_{bs}}{l_b} \cdot A_{b1} \cdot a_1^2$ – coefficient of inelastic stiffness of the joint;

$m_{yield} = \varepsilon_T \cdot E_{bs} \cdot A_{b2} \cdot a_2$ – residual moment.

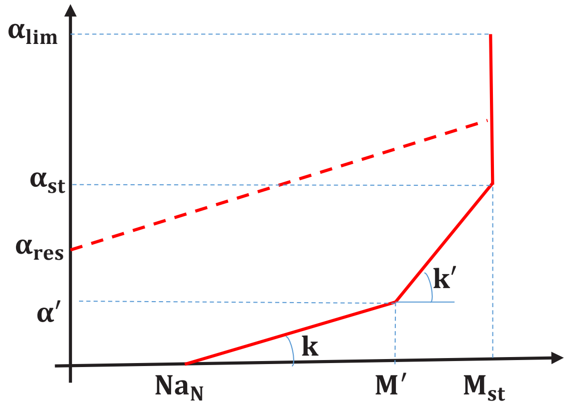
Pic. 3 shows a graph demonstrating the dependence of the angle of rotation of the joint on the magnitude of the bending moment, taking into account equations (10), (14) and (16). If the unloading of the joint is allowed from the moment $M' > M \geq M_{st}$, then the residual angle of rotation α_{res} can be observed in the joint, determined by the residual moment and the rigidity of the bolts of the first row closest to the turning point:

$$\alpha_{res} = -\frac{m_{yield}}{\frac{E_{bs}}{l_b} \cdot A_{b1} \cdot a_1^2}. \qquad (17)$$

Thus, analytical dependences of rigidity of joints and the magnitude of the forces acting in the joint were obtained for correct modelling of rigidity of a connection joint with tensile bonding in prefabricated tunnel linings. The overall rigidity of the lining is formed not so much by the bending rigidity of the cast-iron tubing or reinforced concrete block, but by much less rigid joints, in comparison with which the bending of the lining element can be neglected.

These dependencies in the form of functions $\alpha(N, M)$ can be used directly in finite element analysis computational programs, or taking into account the refined methodology. Let us consider an example of this problem, solved by the finite element method, taking into account the physical nonlinearity of materials and contact nonlinearity.

The joint of two sections of cast-iron tubing with a bolted connection, modelled in the midas FEA environment is shown in Pic. 4. The Table 1 shows the characteristics of the materials in the model. The contact problem is formed by the



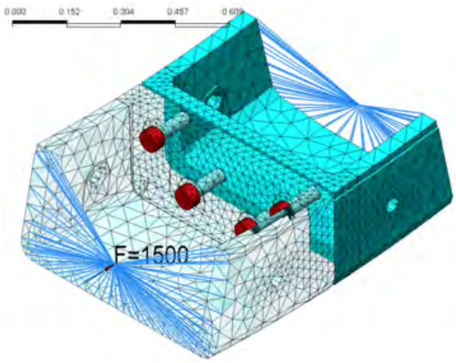
Pic. 3. Graph of the dependence of the angle of rotation of the joint on the moment [developed by the authors].

Table 1

Materials of the joint model [compiled by the authors according to the data of SP.16.13330.2017*]

Elements	Material	Model of the material	Parameters of the model
Tubing	Grey cast iron SCh-20-40	von Mises model	E = 100 hPa ν = 0,1 σ_{yield} = 200 MPa
Bolts	St3	von Mises model	E = 206 hPa ν = 0,2 σ_{yield} = 245 MPa A_b = 13,85 cm^2

* SP [Code of Rules] 16.13330.2017. Steel structures. Updated edition of SNiP [Construction standards and rules] II-23-81* (with Amendments No. 1, 2, 3).



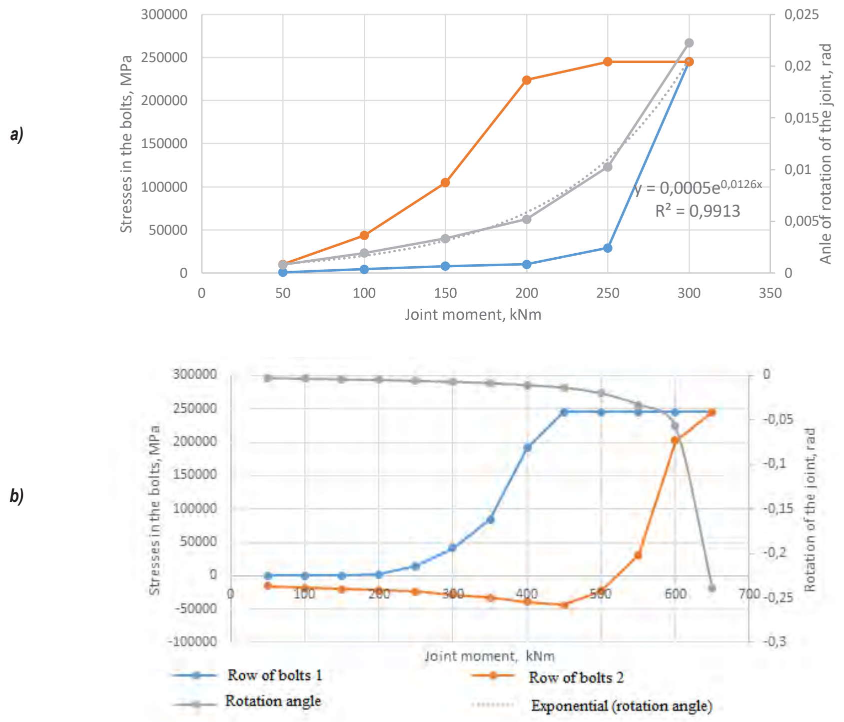
Pic. 4. General view of the model of the joint of sections of tubing [developed by the authors].

standard surface-to-surface contact method with a static friction coefficient of 0,4.

The loadings of the model are taken as positive and negative gradually increasing moments with different longitudinal compressive forces from 0 to 3000 kN with a step of 500 kN. The forces are applied to the ends of the computational domain of the model evenly over the entire surface area by connecting the nodes with a rigid insert.

The results of the modelling show the dependence of the angle of rotation of two tubing sections relative to each other, the stresses in the bolts, the change in the contact area of the tubing sections on the moments acting on the tubing.

Under the action of positive moments that open the gap between the tubing sections from inside the tunnel, a plastic hinge is formed when the design resistance of the bolts in both rows is reached. Pic. 5a shows the change in stresses in the bolts of each row and the increase in the angle of mutual rotation of tubing sections. As an example, graphs are given at zero longitudinal force. Upon reaching a moment of 200 kNm, the



Pic. 5. Deformability of the joint (a – in the absence of a longitudinal force; b – in the presence of a compressive longitudinal force) [developed by the authors].

joint deforms linearly; then first in the far row, and then in the row closest to the turning point, the bolt material passes into the plastic stage and the increase in the angle of rotation increases according to a pronounced exponential law.

In the presence of longitudinal forces, the value of the joint moment *Mst* increases, and the stress distribution in the bolts changes. Pic. 5b shows graphs of the angle of rotation and stresses in the bolts under the action of negative moments that open the joint from the side of the rock. A significant part of the graph up to the moment when plastic deformation begins to occur in the far row of bolts is also linear.

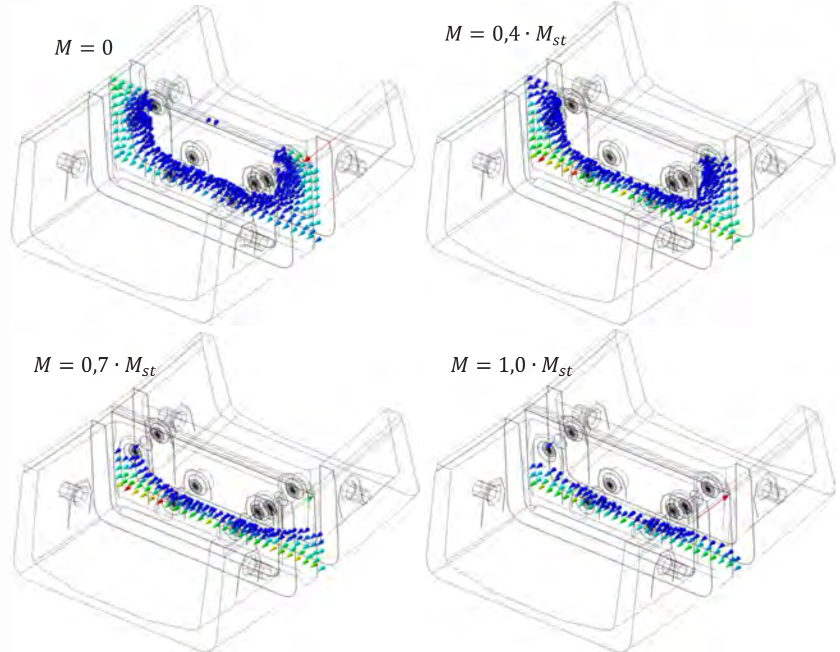
Numerical modelling of joints gives a similar result as compared with the analytical solutions presented in Pic. 3. There are some differences in the «flatness» of the behaviour, which is due to the assumption on a single and rigidly defined point of mutual rotation of the tubing sections. The numerical solution shows that in the presence of a longitudinal compressive force, the contact area of tubing sections is distributed unevenly. The spatial rigidity is such that the area between the longitudinal ribs of the tubing sections is out of contact during axial compression, and the contact tends to the ribs and the back of the elements, as shown in Pic. 6. With an increase in bending moments, the contact area migrates to the back, towards the point *O* in the scheme in Pic. 2, and the force transmitted through the contact increases. A similar picture is observed with application of negative moments when the contact area is located along the longitudinal ribs of tubing sections.

The dependence of the joint rigidity on the longitudinal force and moment according to the results of a numerical experiment is shown in Pic. 7. Within the limits of linear deformations of the bolts, the difference in rigidity is insignificant, i.e., the rigidity of the joints is practically independent of the magnitude of the longitudinal force. Longitudinal forces affect the magnitude of joint moments, as well as rigidity of the joints at significant bending moments approaching the joint moments.

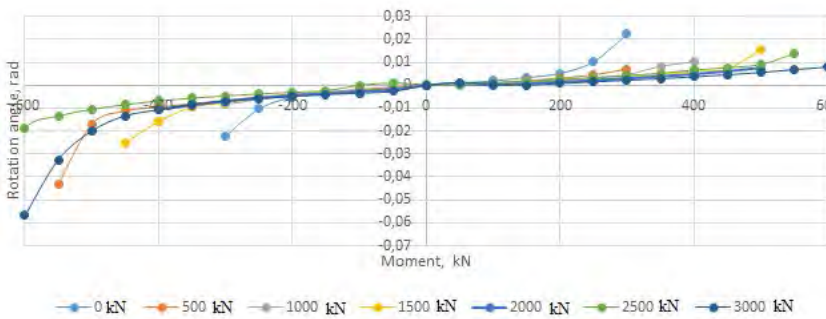
Let us consider the linear parts of rigidity, since the main forces in the lining of tunnels fall on the elastic deformations of the structures. Within the range of the moments of 200–400 kNm, it seems possible to determine the linear functions of the rotation angles $\alpha(N, M)$, as:

$$\alpha(N) = a \cdot M + b, \tag{18}$$

where *a* and *b* – approximation coefficients, given in Table 2.



Pic. 6. Migration of the contact area in the joint with an increase in moment [developed by the authors].



Pic. 7. Rigidity of the joint under various longitudinal forces [developed by the authors].

The parameter *a*, which from equation (11) has the physical meaning of the linear rigidity, varies in the range -25 % … +6 % as the force increases. When calculating the lining of tunnels, complete absence of longitudinal forces is quite rare, therefore, starting from a force of 500 kN, the range of variation is -10 % … +6 %, which is within the engineering error of calculating the load carrying structures of tunnels.

The following conclusions can be drawn from this research:

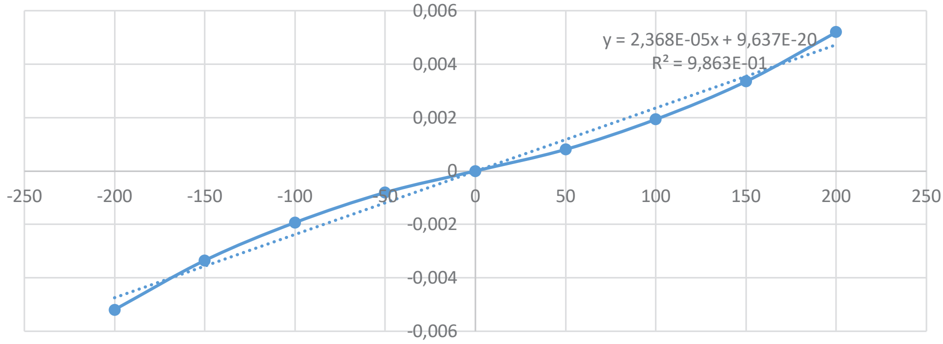
1) rigidity of bolted longitudinal joints with tension bonding slightly depends on the magnitude of the longitudinal force in the joint;

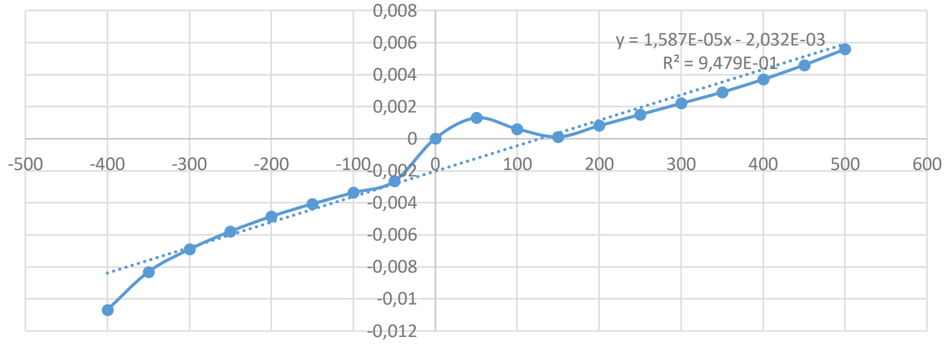
2) within certain limits, the rigidity does not change, and the angle of rotation of the lining elements relative to each other changes linearly depending on the magnitude of the moment in the joint area;

3) with the emergence of plastic deformations in the bolts, the rigidity of the joint drops, and continues to decrease with increase in the moment;

4) the value of the joint moment is determined by the appearance of plastic deformations in the bolts, and the limiting value of the angle of rotation of the elements of the lining is determined by the limiting deformation of the connection furthest from the point of turning of the bolts.

Let's carry out test calculations of the tunnel lining, consisting of cast-iron tubing, using the obtained dependencies. The objective of the calculations is to determine the change in internal forces in the lining without considering rigidity of the joints of the lining elements and considering this rigidity. The calculation is performed as a plane problem in the GTS NX finite element modelling environment for geotechnical





Pic. 8. Linear approximations of rigidity (a – in the absence of a longitudinal force; b – with a compressive force of 3000 kN) [developed by the authors].

Table 2

Parameters of linear approximation of rigidity according to the formula (17) [developed by the authors]

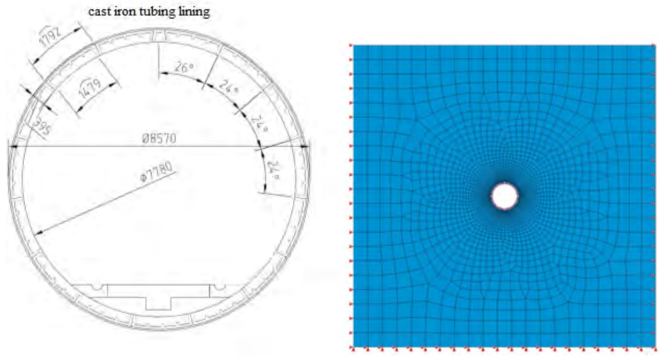
Longitudinal compressive force N	$a \bullet 10^{-5}$	$b \bullet 10^{-4}$	Determination coefficient R^2
0	2,368	0	0,986
500	1,781	3,291	0,99
1000	1,892	10	0,963
1500	1,804	4,832	0,965
2000	1,629	14,55	0,968
2500	1,654	18	0,963
3000	1,587	20,32	0,948

structures. The lining is made of cast-iron tubing sections with an internal diameter of 7,78 m; the location of the tubing joints is shown in Pic. 9.

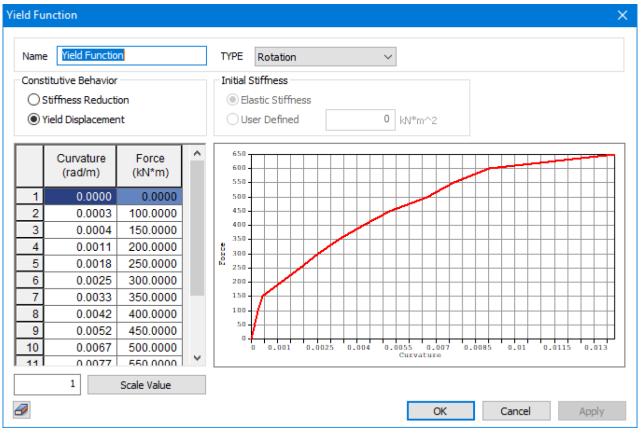
The soils surrounding the lining are modelled using an isotropic Hardening Soil (HS) model implemented in the GTS NX environment. The model accurately describes the behaviour of the soil during excavation of soil, during construction of retaining walls and tunnelling, accompanied by a decrease in the average effective stress and, at the same time, by mobilisation of rock shear resistance [17; 18].

As an example, for the test task, we will take the physical and mechanical properties of soils of three types, given in Table 3. The computational area of the model has dimensions of 100 x 100 m. In the centre, there is a ring retaining the soil mass, which has rigidity of a ring made of cast-iron tubing 0,75 m wide. The calculation is performed in two stages:

1) The initial stage for determining the earth pressure and the initial displacements of the soil mass.



Pic. 9. Railway tunnel lining design and FE model [developed by the authors].



Pic. 10. Properties of an inelastic hinge [screenshot of the GTS NX software window made during simulation process according to authors' model].

2) The second stage, at which the soil is excavated, and the hole is immediately reinforced with a lining. The interface elements of the soil-lining contact were not used.

The view of the finite element model is shown in Pic. 9. The introduction of rigidity of the joints is carried out by assigning a hinge to the node of the finite element of the lining, which has the properties of deformability, as shown in Pic. 7 or according to the linear equation (18). The rigidity of the joint is modelled by the Beam–Lumped property («Beam–lumped hinge»). The inelastic behaviour is described by skeletal curves, which are empirical hysteresis models. Longitudinal rigidity is represented by a spring in the centre of the element, and bending rigidity is represented by springs at the ends of the elements and is described by force-displacement dependencies.

In calculations, it is possible to use the following types of dependences or types of hysteresis models:

– Origin-oriented dependence: reaction points under initial loading and unloading move along a three-linear skeletal curve. This model is used in test calculations.

– It is possible to use other models for further research: Peck, Kinematic, Takeda models, and others.

According to the GTS NX manual[2, 3], the properties of inelastic behaviour are specified in the *Yield Function* in the form of a positive branch of dependences of the angle of rotation *Curvature* (rad/m) on the moment *Force* (kN•m) (Pic. 10). The behaviour at negative moment is calculated automatically. In the process of testing the operation of the function in the GTS NX 2019 v1.2 version on simple models, it was found that when assigning the properties of an inelastic hinge in a plane problem, it is desirable to indicate the direction of the degree of freedom

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[2] Benchmarks & Verifications Manuals. Chapter 3. Material Nonlinearity. MIDAS IT Co,. Ltd. [Electronic resource]: https://globalsupport.midasuser.com/helpdesk/File/Get/3848666. Last accessed 28.02.2022.

[3] GTS NX On-line Manual. Help when working with the program.

Table 3

Physical and mechanical characteristics of soils when using the HS model [compiled by the authors according to the data of [18]]

Soil type	Volumetric weight of soil	The secant modulus of elasticity at 50 % value (σ_1–σ_3) from triaxial tests	Tangential modulus from compression tests	Modulus of elasticity during unloading – reloading from compression tests	Poisson's ratio for unloading - reloading	Compression curve nonlinearity parameter	Lateral soil pressure coefficient	Efficient cohesion from triaxial tests	Effective angle of internal friction from triaxial tests
Designations	γ	E_{50}^{ref}	E_{oed}^{ref}	E_{ur}^{ref}	υ_{ur}	m	K_0	c'	φ'
Measurement unit	kN/m³	MPa			–	–	–	kPa	deg.
Condition No. 1. Silty sandy loam	21,4	12	10,5	36	0,35	0,5	0,642	20	21
Condition No. 2. Sand	15,2	26	19	110	0,3	0,8	0,426	1,0	35
Condition No. 3. Dense clays	22,5	305	191	610	0,2	0,65	0,609	125	23

of the hinge R_z and the I&J components in the *Hinge location* component field.

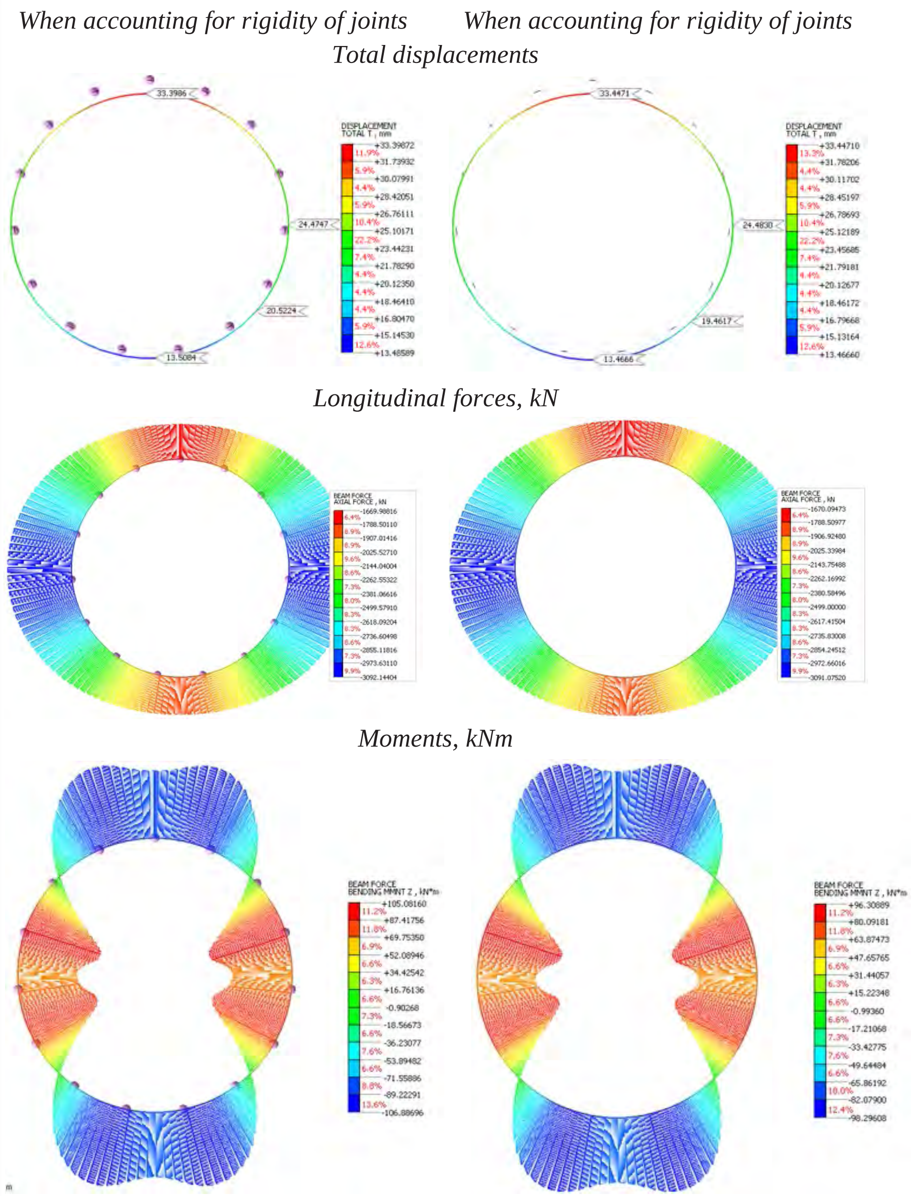
The results of comparative modelling are presented in the form of displacements of the tunnel lining, longitudinal forces and bending moments in it, as shown in Pic. 11 for soil conditions No. 1 (silty sandy loam). For the models that take into account rigidity of joints, the properties of inelastic behaviour are introduced at the locations of the joints of the tubing; the models that do not consider rigidity are completely identical to the first ones do not introduce the inelastic behaviour of the joints.

Comparative modelling has shown that under various soil conditions accounting for rigidity of joints has little effect on total displacement of the linings and the longitudinal forces in them. The main influence is observed in the magnitude of the bending moments, where the presence of inelastic elements with the behaviour of the joint with tension bonding increases the bending moments by 2,2–8,4 %. A more pronounced

Table 4

Results of comparative test calculations [compiled by the authors]

Results		Displacements, mm		Longitudinal forces, kN		Moments, kNm	
Soil conditions	Rigidity of joints	In the crown	In the wall	In the crown	In the wall	In the crown	In the wall
Cond. No. 1	Considered	77,27	51,05	-2216,4	-3279,6	-507,2	+460,1
	Not considered	76,98	51,09	-2217,0	-3279,8	-496,1	+447,4
	Difference	0,4 %	-0,1 %	0,0 %	0,0 %	2,2 %	2,8 %
Cond. No. 2	Considered	16,07	10,8	-1208,6	-2142,2	-155,2	+142,3
	Not considered	16,29	10,85	-1211,5	-2139,8	-144,9	+132,4
	Difference	-1,4 %	-0,5 %	-0,2 %	0,1 %	6,6 %	7,0 %
Cond. No. 3	Considered	33,40	24,47	-1670,0	-3092,1	-106,9	+105,1
	Not considered	33,45	24,48	-1670,1	-3091,1	-98,3	+96,3
	Difference	-0,1 %	0,0 %	0,0 %	0,0 %	8,0 %	8,4 %



Pic. 11. Results of comparative calculations under soil conditions No. 1 [developed by the authors during simulation].

influence is observed at a smaller value of the moments in dense clays.

CONCLUSIONS

Modern methods of calculation of prefabricated tunnel linings, structurally having tensile bonding in the joints, make it possible to consider the bending rigidity of transverse joints when determining the forces. Rigidity equations for this joint have been analytically derived depending on the magnitude of the bending moment, longitudinal force, location and steel grade of the bolts, and joint geometry. The resulting three-linear function describes the dependence of the angle of mutual rotation of the lining elements on the magnitude of the acting forces and shows three main stages of rigidity reduction. The first stage consists in the linear behaviour of all elements and the initial rigidity of the joint. The second stage emerges when the yield limit of the material of the row of bolts farthest from the centre of rotation is reached, characterised by a decrease in rigidity and a residual angle of rotation during unloading. The third stage is the emergence of a plastic hinge.

These considerations have been verified by modelling the joint of two cast-iron tubing sections. The nature of the dependences obtained coincides with the analytical solution. Additionally, linear rigidity equations were obtained for the initial stages of loading the joints, where it is shown that the effect of the longitudinal force on rigidity is rather weak due to the spatial contact area between tubing sections. Graphs of inelastic behaviour based on the results of finite element modelling are introduced as functions for test calculations of tunnel linings.

Comparative calculations of linings with and without accounting for rigidity of joints, all other elements being equal, showed that accounting for rigidity of joints results in an increase in bending moments in the linings by up to 8,4 % under certain soil conditions. At the same time, different soil conditions affect the forces in different ways; in denser soils, the influence of the presence of joints in the calculations increases.

Thus, the proposed approach makes it possible to obtain a more accurate picture of assessment of the stress-strain state of prefabricated tunnel linings with tensile bonding.

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