Development of the effective segmental tunnel lining with flexible elements

DMITRY POLIAKOV
Department of bridges, tunnels and construction
Moscow State Automobile and Road Construction University
64 Leningradsky Prospect, Moscow
RUSSIAN FEDERATION
piroxinit@mail.ru
VLADIMIR POLIAKOV
Institute of Track, Construction and Structures
Moscow State University of Railway Engineering (MIIT)
9b9 Obrazcova Street, Moscow
RUSSIAN FEDERATION
pvy55@mail.ru

Abstract: This article describes a series of experiments aimed on effective configuration of a reinforced concrete circular segmental lining with flexible elements in radial joints.

Key-Words: tunnel circular segmental lining, stress-strain state, flexible elements, reinforced concrete.

1 Design solution

Tunnel boring machines are becoming more and more common in modern tunneling. They can be used in a large variety of soil conditions, ensure safety for personnel and operate under considerable subterranean water pressures [1,2]. Since most TBMs have a circular cross-section, circular tunnel linings became a very common design for tunnels. Consequently, development of more effective circular tunnel lining design can prove to be useful. Efficiency of a tunnel lining is determined by its durability, waterproofness and material expenditure.

Of all circular linings, circular segmental reinforced concrete (SRC) linings are currently the most common design solution. The technology of production is well-established and sophisticated TBMs are used to assemble these linings. Waterproofing of the lining can be ensured by rubber sealants.

SRC linings are generally rigid and have a high carry capacity, but their rigidity leads to appearance of high stresses in the lining. Even if the joint does not have any constant bolts or other tension connections, in most cases high axial force prevents the joints from opening. The shortcoming of SRC linings is cracking of concrete in radial joints that is caused by stress concentration on segment edges.

To resolve this problem an alternative SRC lining design is proposed – the segmental lining with flexible elements. These elements are placed in radial joints of the segmental lining, creating areas of decreased bending stiffness within the ring. The elements partially redistribute the stress from the lining to the soil massive on the sides of the tunnel. It is presumed, that a design like that would allow decreasing of bending moments in the ring and, consequently, decreasing of material expenditure.

2 The experimental model

To prove the efficiency of the new lining, a line of experiments has been carried out. Since the concept has never been constructed before, a finite-element model experiment has been implemented to determine the efficient configuration of the lining with flexible elements.

The object of the experiment is a binary system that includes the lining and the soil mass that is surrounding it. The model had to take into account several aspects of the system:

Elastoplasticity of the soil mass. Most types of soils are anisotropic, tend to change their stiffness when compressed and can hardly resist even small tensile stresses. When modelling a subterranean structure, it is essential to take into account the realistic stress-strain dependence, especially when a flexible lining that works together with the soil around it is to be developed. To describe the above mentioned and other specific properties of soils, a sophisticated mathematical model is required. According to certain researches [3], the Hardening soil model is able to take into account these properties. The model has different nonlinear stress-strain functions for spherical and deviatoric stresses. Stiffness is defined using 3 stress-dependent stiffness modules – primary loading stiffness E_{50}, oedometer stiffness E_{oed} and unload/reload stiffness E_{ur} [4]. These modules are represented of fig. 1, q stands for the deviatoric stress. These modules allow to take into account the anisotropy and changes of soil properties caused by compression. The dependence between the reference stiffness for each soil and exact stiffness in each point is described by equations:

$$E_{50} = E_{50}^{ref} \cdot \left(\frac{c \cdot \mathrm{ctg}\varphi + \sigma'_3}{c \cdot \mathrm{ctg}\varphi + p^{ref}} \right)^m \qquad (1)$$

$$E_{oed} = E_{oed}^{ref} \cdot \left(\frac{c \cdot \mathrm{ctg}\varphi + \sigma'_1}{c \cdot \mathrm{ctg}\varphi + p^{ref}} \right)^m \qquad (2)$$

$$E_{ur} = E_{ur}^{ref} \cdot \left(\frac{c \cdot \mathrm{ctg}\varphi + \sigma'_3}{c \cdot \mathrm{ctg}\varphi + p^{ref}} \right)^m \qquad (3)$$

So, elasticity in each exact point of soil is dependant from friction angle φ, cohesion c, power for stress-level dependency of stiffness m, and horizontal stress σ_3. These modules can be determined using triaxial stress-strain curves [5].

Determination of the gravity stresses. It is essential for the model of the binary “lining-soil” system to take into account the fact, that the excavation of the tunnel is being undertaken in a soil massive that appeared long before the excavation. The above mentioned Hardening soil model allows estimating the stresses, strains and stiffness as functions of depth and soil properties in any point of the soil mass. But it is important to note, that a certain field of stresses (and, consequently, strains and stiffnesses) is formed in the soil by the time when the excavation reaches it. It means that the model has to include a stage that allows determining the natural stress-strain field and then use it as initial conditions for the second stage, when the lining appears. Some modern software allows to create a finite-element model that may change in time or when some other criterion is reached.

Friction between the lining surface and the soil massive. Friction force between soil and a hard body surface is difficult to describe with a friction coefficient, but it can be determined through parameters of soil. It is presumed, that cohesion between the surface and soil is too small to consider, so friction generally depends on the friction angle of the soil. According to the Russian regulations [6], the friction angle of the soil itself and the friction angle on the contact surface are connected with a multiplier indicated in table 1.

$$\gamma_k = \frac{\varphi_{interface}}{\varphi_{soil}}$$

$$R_{\mathrm{inter}} = \frac{\tan \varphi_{interface}}{\tan \varphi_{soil}}$$

Equations 4 and 5 allow to determine the friction angle on the contact surface.

All the above mentioned means of modelling can be performed using PLAXIS.

Table 1

Material	Technology and curcumstances	γ_k
Concrete, reinforced concrete	Monolithic massive and thin retaining walls, that are cast into a dry fromwork. Monolithic foundations	0,67
	Monolithic thin retaining walls, that are cast into a bentonite slurry in a naturally moistened soil. Prefabricated walls, foundations and other elements	0,50
	Monolithic thin retaining walls, that are cast into a bentonite slurry in a saturated soil.	0,33
Wood, metal	In small-grained or dusty saturated sand	0
	Other soils	0,33

3 The experiment

The aim of the experiment is to estimate the efficiency of the lining with flexible elements and define the recommendations for its design. Efficiency of the lining is defined by 3 main criteria:

- Durability
- Waterproofness
- Material expenditure

In the current article, only the third criterion is revealed. To prove the lining's efficiency it is necessary to compare the expenditure of the lining with flexible elements to that of a conventional lining in similar conditions. Generally, the lining segment's material expenditure is defined by the axial force and bending moment. So these are the main parameters to control during the experiment.

It is necessary to determine the properties of the flexible elements and their positions in the ring that provide efficiency. Since the segments of the lining are prefabricated reinforced concrete elements, their properties will be similar to those of the conventional lining to estimate the impact of the flexible elements. To define the elements it is necessary to determine their stiffness and measurements, so these two parameters will be variable throughout the experiment. It is vivid to indicate stiffness of flexible elements as relative stiffness - a proportion of bending stiffness of the lining to that of the flexible elements.

The experiment operates with a 10 m diameter lining placed in clay. Five linings have been examined – a rigid conventional lining and four linings with flexible elements, each with a specific element disposition (fig. 2).

Also, for schemes 1-4 the stiffness of flexible elements was variable. The graphical representation of the function between the bending moment and the relative stiffness for schemes 1-4 is shown on fig. 3, the bending moment in a conventional lining is also shown for comparison. These charts indicate that if the flexible element is located in the same section of the ring, in which the conventional lining forms the maximal bending moment, the bending moment in the lining with flexible elements would be considerably lower, than that in the conventional lining. The experiment showed, that in scheme 4 the maximum bending moment for relative element stiffness 5% is 50% lower, than that in a conventional lining, which is a substantial result. The axial force decreased in 5%, compared to a conventional lining. When the relative stiffness was decreased further, it turned out that the shape of the bending moment diagram started to change (fig. 4). Case a stands for scheme 4 with relative stiffness 1.5%. The shape of the bending moment diagram is close to that in a conventional lining. In case b the same lining with relative stiffness 0.5% showed, that the peak points of bending moments moved from the flexible elements towards the centers of the rigid segments. This allowed presuming, that another 4 elements would decrease the bending moments further, since placing the elements in peak moment points proved to be effective. Scheme 5, which includes 8 flexible elements and its bending moment diagram for relative stiffness 0.2% are shown on fig 6. In this case the peak points are located in the middles of the segments and the maximum bending moments are 90% lower, than those in a conventional lining. Strength analysis for this type of lining allows decreasing of lining thickness in 50% and total reinforcement section square in 64% taking into account the absence of cracking. The chart shown on fig. 7 reveals the dependence of the maximum bending moment in a ring from relative stiffness for scheme 4 and 5. It is evident from fig. 7 that the strongest decrease in bending moments can be observed on the interval 0,05..0,5% of the relative stiffness, which is the optimal stiffness for design. Nevertheless, when relative stiffness is decreased further and reaches 0,05%, the deformation between the top and bottom points of the ring begins to increase.. Decrease of the relative stiffness leads to decrease of bending moments while increase of the relative stiffness leads to decrease of top-bottom convergence. As a result of a 2-criteria optimization [7], the optimal relative stiffness lies within interval 0,1..0,5%.

Further experiments indicate, that this interval is not dependent from the depth of the tunnel, its diameter, but is dependent from soil properties. The bending moments in the lining with flexible elements placed in clay or loam are about 40% higher, than in a same lining placed in sand. The strains also proved to be about 55% higher for sand, than that for clay and loam. It was also determined, that the size of the elements has relatively small impact on the bending moments, compared to the impact of the relative stiffness. Thus, since the cost of the elements may prove to be considerable, small size is an advantage.

4 Conclusion

The experiment leads to the following conclusions:

- The most effective configuration of a circular SRC tunnel lining with flexible elements is a symmetric ring with 8 flexible elements that are evenly distributed with the first element on the top point. Relative stiffness of the flexible elements should be within interval 0,1..0,5%
- The peak bending moments in the ring of a SRC tunnel lining with 8 flexible elements are 90% (80% - for 4 elements) lower in

comparison with the conventional SRC tunnel lining.

The lining with flexible elements shows efficiency in terms of material expenditure compared to the conventional reinforced concrete lining. It can be used for various diameters of tunnels in clays, loams, and in some cases, sand clay.

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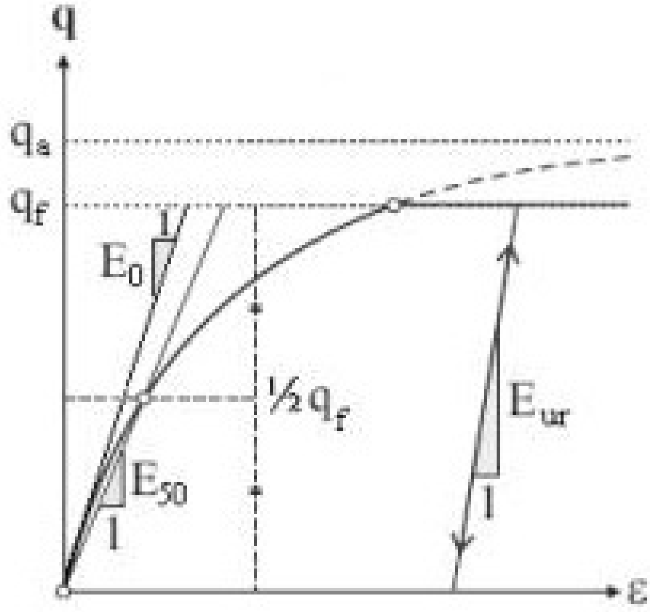


Figure 1. Graphical representation of hardening soil model stiffness modules

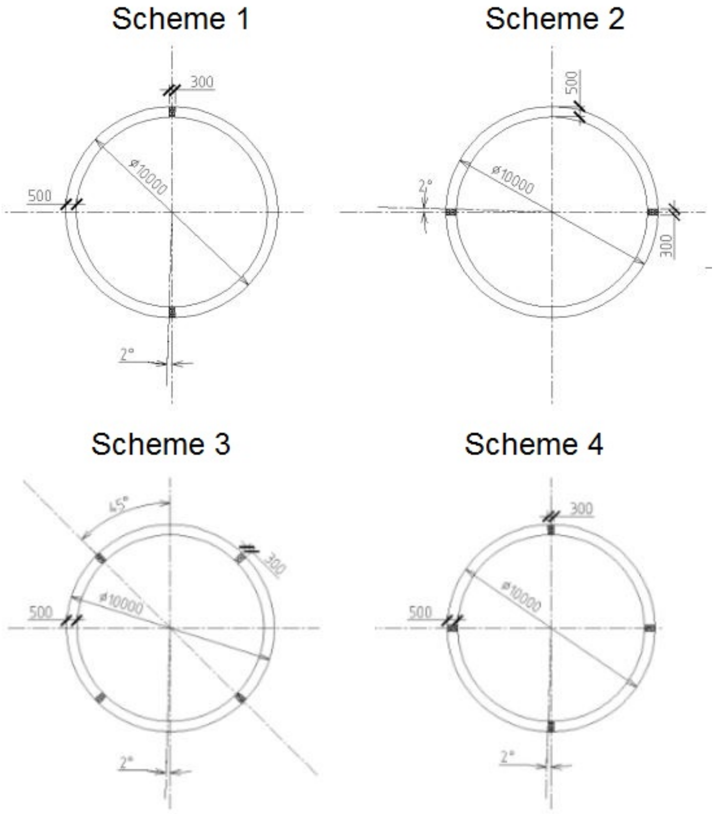


Figure 2. Experimental schemes of lining rings with flexible elements

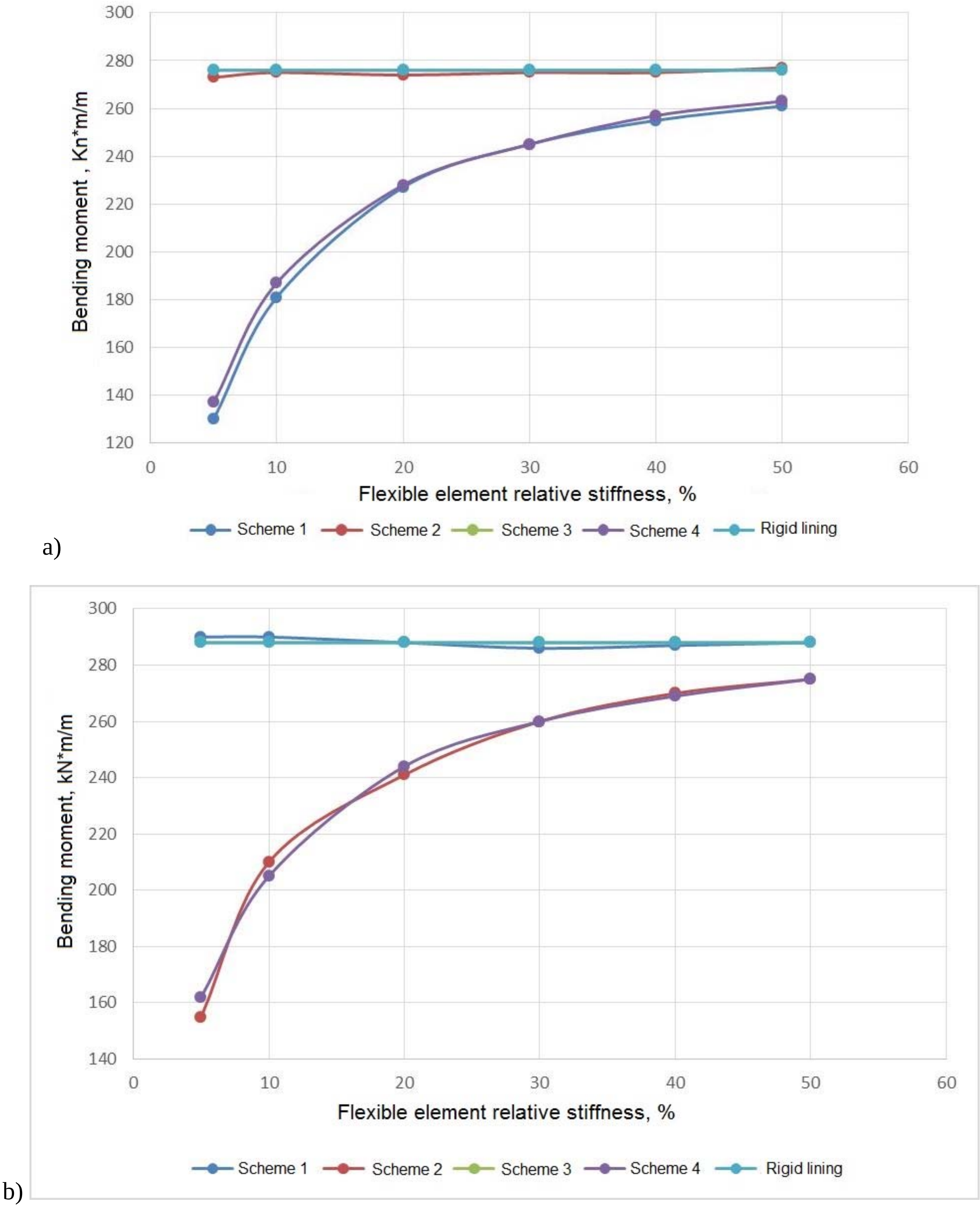
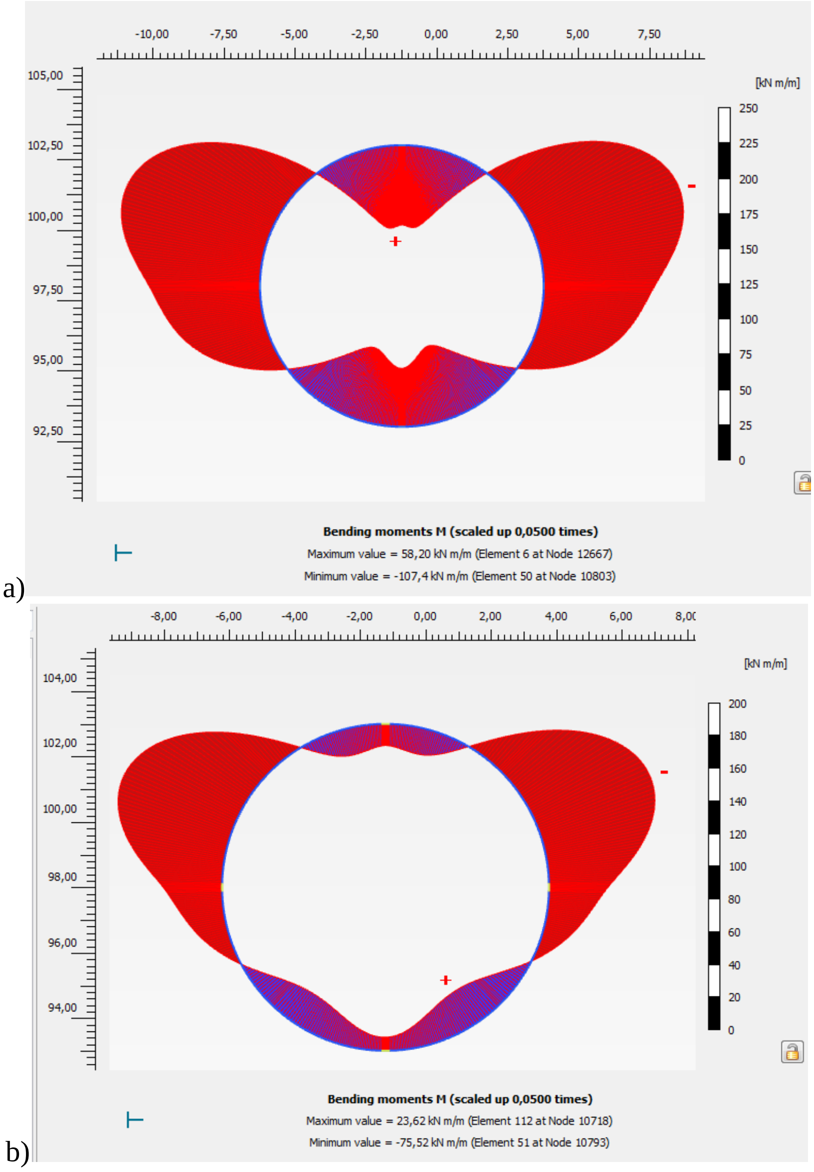


Figure 3. Graphical representation of the function between the bending moment and the relative stiffness for schemes 1-4



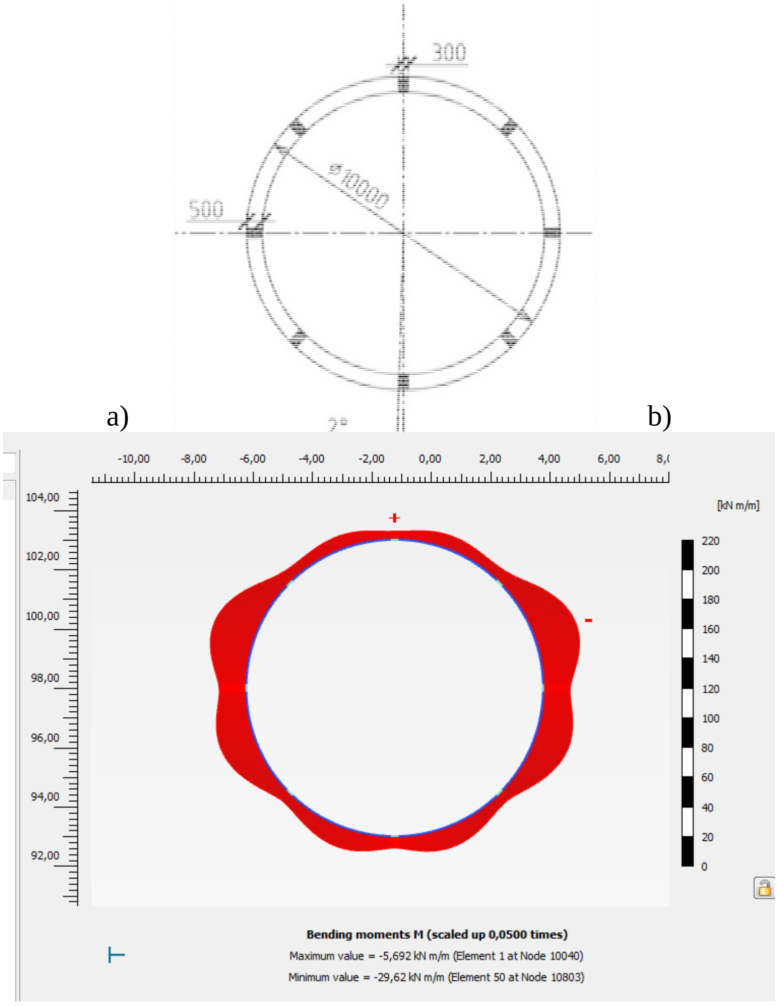
Bending moments M (scaled up 0,0500 times)
Maximum value = 58,20 kN m/m (Element 6 at Node 12667)
Minimum value = -107,4 kN m/m (Element 50 at Node 10803)

a)

Bending moments M (scaled up 0,0500 times)
Maximum value = 23,62 kN m/m (Element 112 at Node 10718)
Minimum value = -75,52 kN m/m (Element 51 at Node 10793)

b)

Fig 4 Bending moment diagrams of scheme 4 lining ring for relative stiffness 1,5% (a) and 0,5% (b)



Bending moments M (scaled up 0,0500 times)

Maximum value = -5,692 kN m/m (Element 1 at Node 10040)

Minimum value = -29,62 kN m/m (Element 50 at Node 10803)

Figure 5. Scheme 5 (a) and its bending moment diagram for relative stiffness 0,2% (b)

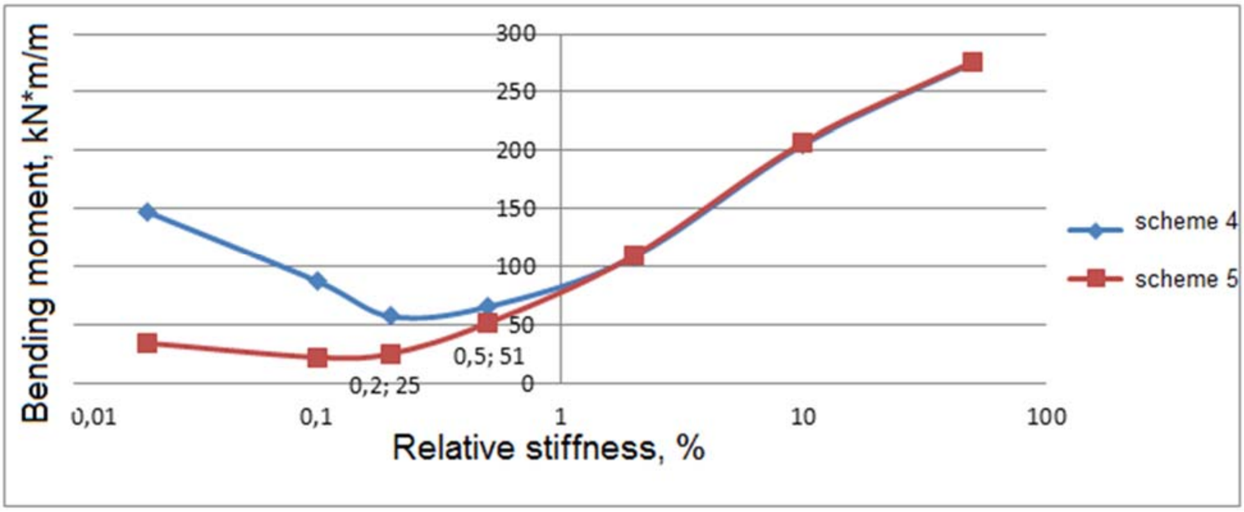


Figure 6. Graphical representation of the function between the bending moment and the relative stiffness for schemes 4 and 5.