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STRENGTHENING AND WATERPROOFING SOLUTIONS FOR BELGRADE RAILWAY TUNNELS: CASE STUDY

Summary: Water ingress is a major cause of deterioration in underground tunnel structures, particularly in ageing railway systems. This study presents the proposed solution for the rehabilitation of the Belgrade underground railway tunnel system, emphasizing both waterproofing and structural improvement. The analysis is based on real geological, geotechnical, structural, and survey data, as well as field inspection findings on lining condition. Special attention is given to the application of fibre-reinforced shotcrete (FRS) as a combined solution for strengthening and reducing permeability. The proposed approach also includes adhesive waterproofing coatings and repair of cracks and leakages using injection materials. The results demonstrate improved watertightness and structural safety.

Keywords: fibre-reinforced shotcrete, tunnel rehabilitation, waterproofing, structural strengthening

OJAČANJE I HIDROIZOLACIJA ŽELEZNIČKIH TUNELA U BEOGRADU: STUDIJA SLUČAJA

Rezime: Prodor vode predstavlja jedan od glavnih uzroka degradacije podzemnih tunelskih konstrukcija, naročito kod starijih železničkih sistema. U radu je prikazano predloženo rešenje za sanaciju tunela u okviru beogradskog železničkog čvora, sa fokusom na unapređenje hidroizolacije i nosivosti konstrukcije. Analiza je zasnovana na realnim geološkim, geotehničkim i konstruktivnim podacima, kao i na rezultatima terenskih pregleda stanja tunelske obloge. Posebna pažnja posvećena je primeni mikroarmiranog mlaznog (tj. torkret) betona (SFRS) kao integrisanog rešenja za ojačanje i smanjenje vodopropustljivosti. Predloženi pristup uključuje i primenu hidroizolacionih premaza i injektiranje pukotina. Rezultati ukazuju na značajno poboljšanje vodonepropustljivosti i unapređenje stabilnosti konstrukcije.

Ključne reči: mikroarmirani mlazni beton, sanacija tunela, hidroizolacija, konstruktivno ojačanje

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1. INTRODUCTION

Underground railway tunnels constructed using conventional methods with cast-in-place reinforced concrete linings are increasingly affected by long-term degradation. The most significant deterioration mechanisms include water ingress through joints and cracks, chemical attack from aggressive groundwater components, and mechanical ageing caused by traffic-induced cyclic loading and stress redistribution in the surrounding ground [1], [2], [3], [4].

Modern tunnel rehabilitation strategies rely on integrated systems that combine structural strengthening with advanced waterproofing. Fibre-reinforced shotcrete (FRS) has become a widely accepted solution due to its capacity to improve post-cracking behaviour, increase ductility, and effectively control crack propagation [1], [4], [5]. Concurrently, spray-applied waterproofing membranes represent an efficient method for mitigating water ingress and protecting the primary structure from long-term moisture exposure [6].

A representative example of this approach is the Gotthard Base Tunnel, along with tunnel systems on Japanese expressways such as the Tokai–Kanjo Expressway. In these projects, integrated composite systems consisting of a primary lining, waterproofing membranes, and fibre-reinforced shotcrete have been successfully implemented [7].

Numerical modelling of tunnel rehabilitation requires an accurate representation of both the construction history and the existing stress states. In this study, a staged excavation and construction approach is adopted to simulate the original tunnel construction process, followed by the subsequent deterioration and rehabilitation phases. The model specifically accounts for the removal of the degraded concrete layer and its replacement with a high-performance fibre-reinforced shotcrete lining.

2. CASE STUDY AND NUMERICAL MODELLING

The Belgrade railway junction is an operational railway system within the Belgrade rail network, formally developed from 1972 as part of a long-term transport infrastructure programme aimed at improving railway connectivity in the city [8]. The Belgrade underground railway network comprises several tunnels, including the "Dedinje" Tunnel, which consists of twin tubes with a horseshoe-shaped cross-section and was constructed in 1975 using conventional tunnelling methods with a cast-in-place concrete lining. The total length of these two tunnel tubes is approximately 6 km. Over its service life, the tunnel lining has exhibited signs of deterioration, primarily associated with water ingress and the degradation of joint injection materials, thereby indicating the necessity for rehabilitation interventions.

Numerical modelling was performed using PLAXIS 2D Advanced software based on a nonlinear finite element approach. The geotechnical parameters of the surrounding ground were derived from archival design documentation, while the soil behaviour was modelled using the Hardening Soil constitutive model. For the purposes of this study, archival design documentation [8], results of site investigation work, geodetic data, and laboratory testing of concrete cores were used.

During the site inspections, the "Dedinje" tunnels were thoroughly examined, revealing varying degrees of lining deterioration, which primarily depend on the specific geotechnical conditions of the surrounding environment. As illustrated in Figure 2, certain lining segments exhibit significant deterioration requiring intervention. Author's field observations indicate that despite the structural integrity of the concrete, the lining is compromised by water ingress through expansion and segment joints. In areas with more pronounced leakage, alterations such as calcification and significant mineral deposits were observed.

A staged construction approach is used to simulate excavation, lining installation, degradation, and rehabilitation. The rehabilitation scenario includes removal of approximately 10 cm of deteriorated concrete and replacement with fibre-reinforced shotcrete.

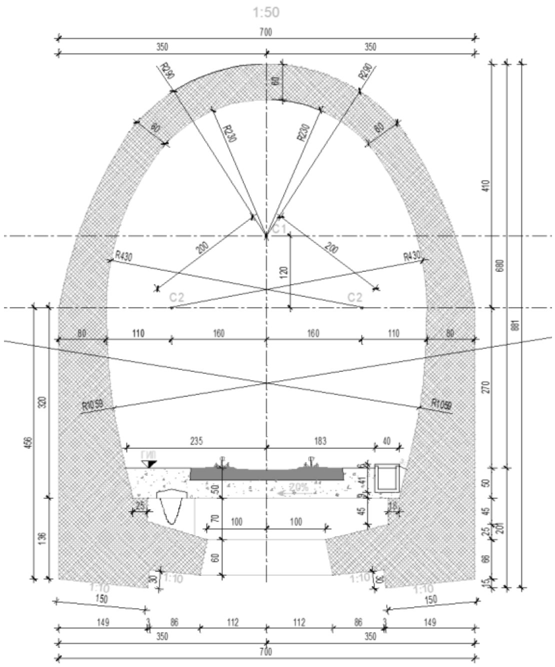

Figure 1: Typical cross-section according to the archival design project

Figure 2: Photographs of the tunnel lining (private archive)

3. STRENGTHENING STRATEGY USING FIBRE-REINFORCED SHOTCRETE

Steel fibre-reinforced shotcrete SFRS is introduced as a structural strengthening material aimed at improving the residual load-bearing capacity of the existing tunnel lining. The addition of steel or synthetic fibres enhances post-cracking behaviour by bridging microcracks and redistributing tensile stresses within the cementitious matrix [1], [2]. Different geometries of steel fibres for concrete and mortar reinforcement are shown on Figure 3 [9].

Unlike conventional reinforced concrete, where discrete steel bars provide primary tensile resistance, fibre reinforcement creates a quasi-homogeneous composite material in which stress transfer occurs at a microstructural level. This results in improved ductility and enhanced energy absorption capacity under both static and dynamic loading conditions [4].

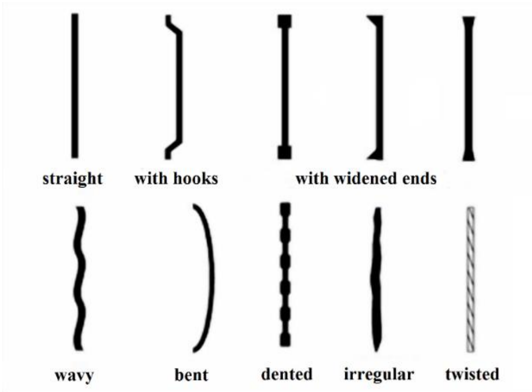

Figure 3: Different geometries of steel fibres

From a structural perspective, the application of fibre-reinforced shotcrete in tunnel linings leads to a reduction in crack width development and improved redistribution of internal forces. This is particularly important in existing tunnels where reinforcement is not easily accessible or where additional conventional reinforcement is not feasible. The effectiveness of fibre reinforcement has been extensively documented in both experimental and analytical studies, particularly in the context of tunnel engineering and shotcrete applications [5],[10],[11],[12]. In rehabilitation scenarios, its primary function is not to fully replace existing reinforcement but to enhance the overall composite behaviour of the lining system.

4. WATERPROOFING SYSTEMS AND WATER PROTECTION MEASURES

In addition to structural strengthening, waterproofing represents a critical component of tunnel rehabilitation. Water ingress not only accelerates material degradation but also contributes to loss of durability and serviceability of tunnel linings [16]. Field investigations identified water-related deterioration as the dominant damage mechanism, manifested through seepage, calcification, and progressive degradation of joint sealing systems. Based on the observed water intensity and structural anomalies, the tunnel lining degradation was classified into five distinct zones (Figure 2).

During the inspection of the left and right tubes of the “Dedinje” tunnel, these water-related issues were observed at construction and expansion joints, in some places extending over lengths of several hundred meters. Certain sections exhibited widespread intensive dripping across the lining surface, accompanied by heavy calcified encrustations. However, because no major structural instability was identified and the recorded clearance profiles showed no deformation, all observed damage is classified as local and non-structural. Crack-type damage does not compromise the stability of the lining, and within limestone geological sections these cracks remain generally dry. To precisely isolate the root causes and verify the exact origin of the water, detailed chemical analyses of seepage water and concrete core testing were performed.

Although severe leakage is present, geotechnical investigations did not confirm a permanent groundwater table, indicating that inflows primarily originate from infiltrated surface water migrating through the fractured rock mass. Due to this spatially variable water distribution, conventional drainage measures were considered insufficient, and a multi-stage waterproofing and sealing strategy was adopted.

Classification of tunnel lining degradation zones based on water ingress severity:
- Zone 1 – Negligible seepage (stable condition, no significant ingress)
- Zone 2 – Minor ingress (localized dampness along joints)
- Zone 3 – Intensive seepage (active leakage with calcification)
- Zone 4 – Critical condition (severe inflow, audible water flow, deposits)
- Zone 5 – Crack-induced damage (longitudinal cracks, non-structural)

In zones with active leakage (Zones 1–4), construction and segmental joints are treated using polyurethane (PU) injection. PU materials are selected due to their rapid reaction with water, high expansion capacity, and ability to seal active flow paths under pressure (approximately 1–4 bar). Injection is performed through packers installed at an angle of approximately 45° to the joint, using a staged and sequential injection protocol to ensure complete filling of voids behind the lining. Secondary injection using acrylic gel is subsequently applied within finer discontinuities to achieve long-term sealing and improved penetration of microcracks and pores.

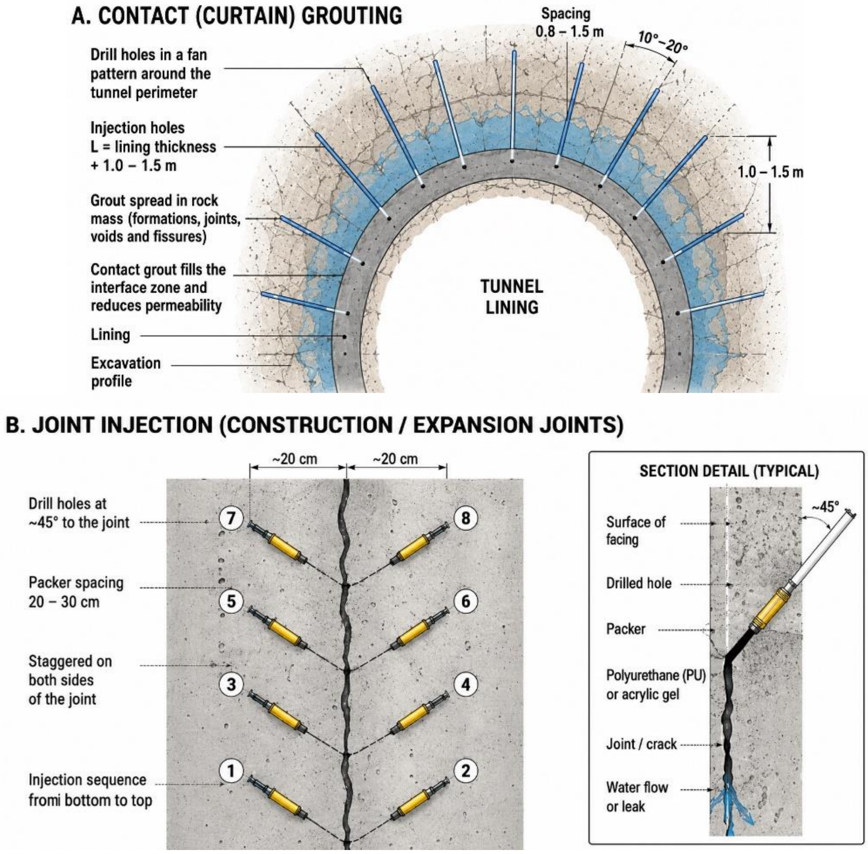

Figure 4: Schematic presentation of contact grouting and joint injection

The first step involves full-surface contact grouting at the lining–ground interface to reduce permeability and close preferential flow paths within the surrounding rock mass. The primary waterproofing system consists of a spray-applied, elastically bonded membrane applied to the prepared concrete substrate. The membrane is designed to be continuous, flexible, and capable of withstanding a negative water pressure of at least 5–6 bar, ensuring reliable performance under hydrostatic inflow conditions. Adhesion to the substrate exceeds 1 MPa, ensuring composite action with the concrete lining. Furthermore, the system is chemically resistant and durable under cyclic wetting, freeze–thaw exposure, and long-term moisture conditions.

Proper surface preparation includes removal of degraded concrete, cleaning of joints, and treatment of active leakage zones prior to membrane application.

The interaction between spray-applied waterproofing and fibre-reinforced shotcrete (FRS) is essential for long-term performance [6]. Proper adhesion and compatibility ensure that hydraulic pressures are not transferred directly to the structural lining, thereby reducing the risk of crack propagation and subsequent leakage development. Additional improvements in impermeability are achieved through mineral additives in the shotcrete, which enhance pore refinement and self-sealing through crystallization in the presence of moisture. Following membrane installation, a protective FRS layer prevents mechanical damage and microcracking, while anchor penetrations and local defects are sealed using targeted acrylic injection.

The combined system of contact grouting, PU and acrylic injection, sprayed waterproofing membrane, and protective shotcrete layer provides an integrated and durable solution for improving watertightness and long-term serviceability of the tunnel lining (Figure 4).

5. NUMERICAL RESULTS AND DISCUSSION

The geological profile used includes weak claystone and marl formations, which contribute to non-uniform loading conditions. Over time, the tunnel lining has been exposed to moisture ingress primarily due to deterioration of waterproofing systems and construction joints. The Laboratory testing of concrete cores indicates that compressive strength remains within acceptable limits, while durability-related degradation is more pronounced. Based on these observations, the proposed rehabilitation strategy includes removal of degraded concrete layers, application of fibre-reinforced shotcrete, installation of waterproofing systems, and use of mineral based materials. This integrated approach addresses both structural and hydraulic deficiencies of the existing tunnel system.

A key aspect of the numerical simulation (Figure 5) is the representation of the existing tunnel, which was constructed using a conventional sequential excavation method. Due to the historical construction process, the current stress state in the surrounding ground cannot be realistically reproduced without considering the full construction history of the structure. For this reason, a staged construction approach is adopted in the numerical model, allowing for the gradual development of stresses and deformations in the soil–structure system.

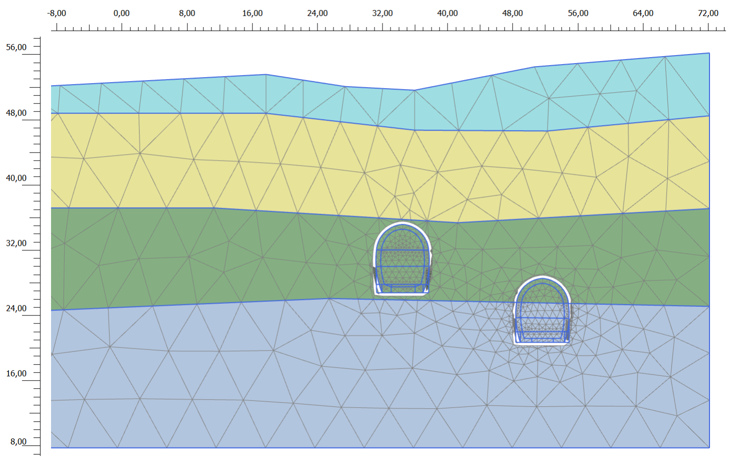

Figure 5: Numerical model in PLAXIS 2D

5.1. INPUT DATA AND NUMERICAL MODELLING STRATEGY

The numerical analysis focuses on a specific tunnel section selected for its complex geotechnical conditions, characterized by highly weathered claystone and marls at a depth of approximately 15 m. To ensure a realistic representation of the stress-strain state, staged modelling was employed using the Deconfinement (1–β) method [13]. This approach simulates the gradual stress relief during excavation, which is critical for capturing the arching effect across the following geological sequence:

- Q2I (Loess and Buried Soil): surface deposits primarily composed of silt-sized particles, modelled using the Hardening Soil constitutive model (E50,ref = 22 MPa),
- M3,2,GL (Marly Clays and Clayey Marls): stiff, low-compressibility Pannonian deposits that act as hydrogeological insulators, where water presence is restricted to fracture networks. These were simulated using the Hardening Soil model (E50,ref = 60 MPa and Eur,ref = 180 MPa),
- M3,1,KL (Marly Limestone Complex): an irregular, jointed alternation of karstified organogenic limestones and marls. Acting as a hydrogeological conductor, this formation is the primary source of groundwater ingress. It was represented using the Hoek-Brown criterion (GSI = 36, σ,ci = 20 MPa).

In order to capture the long-term interaction between the lining and the surrounding ground, a non-standard but recommended modelling approach is employed for the tunnel lining, in which the structural lining is represented using a material soil model Concrete. This approach enables a more realistic simulation of stress redistribution and deformation compatibility between the lining and the surrounding ground, particularly in cases where long-term degradation and reconstruction are considered.

The interface between the concrete lining and the surrounding rock mass is explicitly defined in the model to distinguish structural elements from geotechnical soil elements. The interface between these soil elements is introduced to control the transfer of shear stresses and to accurately represent possible slip and separation effects along the contact surface between the lining and the rock mass. Modelling of FRS layer is done in the same manner with appropriate concrete properties according to real laboratory tests [14].

Table 1: Material parameters for Concrete and fibre-reinforced shotcrete (PLAXIS 2D)

Parameter	Unit	Value	Fibre-reinforced shotcrete
Material model	–	Concrete	Concrete
Drainage type	–	Drained	Drained
γ (unit weight)	kN/m³	25.0	25.0
$E_{(28)}$ (Young's modulus)	kN/m²	30×10^6	36×10^6
$f_{(c,28)}$ (compressive strength)	kN/m²	25×10^3	48×10^3
ν (Poisson's ratio)	–	0.20	0.20
$f_{(t,28)}$ (tensile strength)	kN/m²	2.6×10^3	4.0×10^3
$G_{(c,28)}$ (compressive fracture energy)	kN/m	30.0	30.0
$G_{(t,28)}$ (tensile fracture energy)	kN/m	0.10	0.50
$\varphi_{(max)}$ (friction angle)	°	37.0	38.0
ψ (dilatancy angle)	°	4.0	0.7
γ_{fc} (strength factor)	–	1.0	1.0
γ_{ft} (tensile factor)	–	1.0	1.0
α_{duc} (ductility parameter)	–	20.0	0.6
R_{inter} (interface reduction factor)	–	0.80	0.95

Following the reconstruction of the initial stress state and construction phases, a subsequent modelling step is introduced in which a degraded portion of the existing concrete lining is removed. The structural response before and after this intervention is then compared in terms of stress redistribution and deformation behaviour, allowing for a direct evaluation of the effectiveness of the proposed rehabilitation strategy. As a result, the volumetric forces are presented before and after the intervention and calculation of the needed reinforcement. Replacement of a portion of the lining with a 10 cm thick layer of fibre-reinforced shotcrete containing steel fibres, together with a re-evaluation of the required reinforcement based on the internal forces in the lining after the intervention, has shown that a redistribution of internal forces occurs, along with an improvement in the mechanical properties of the lining, thereby enabling the resistance of tensile stresses without the use of additional reinforcement.

Structural forces in volumetric elements - tunnel lining before rehabilitation:

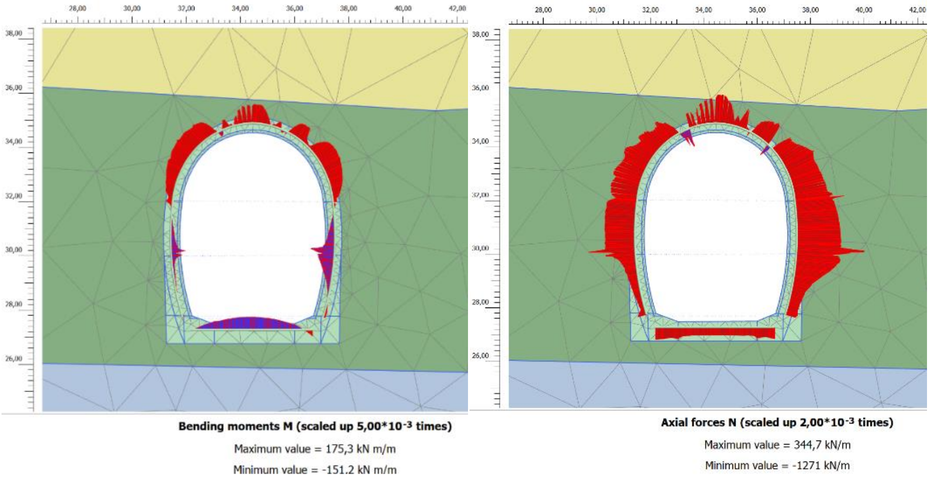

Figure 6 and 7: Structural forces in volumetric elements of the tunnel lining before rehabilitation: bending moments (left) and axial forces (right)

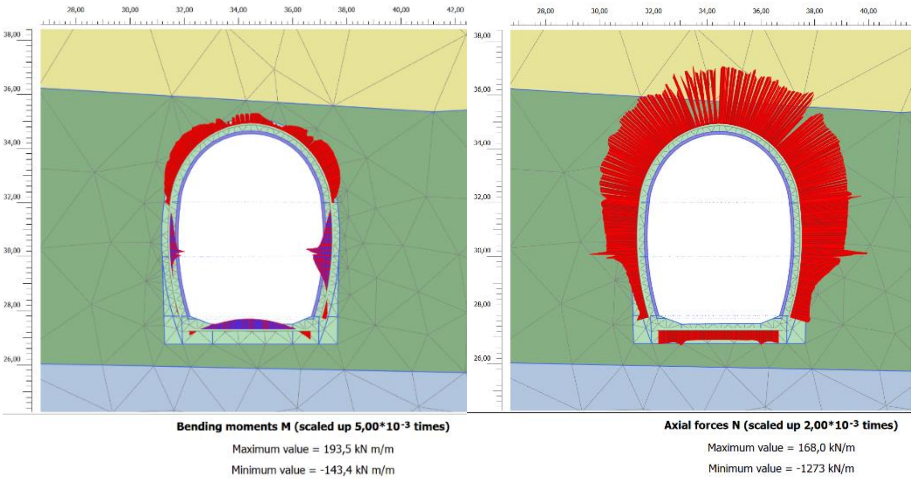

Figure 8 and 9: Structural forces in volumetric elements of the tunnel lining after rehabilitation: bending moments (left) and axial forces (right)

Figures 6 and 7 present the current condition of the tunnel lining in the section requiring significant rehabilitation. Based on site photographs taken by the author during inspection, the lining is found to be structurally stable; however, visible deterioration is present, primarily caused by water ingress through construction and expansion joints, particularly at segment interfaces. Structural forces in volumetric elements-tunnel lining after rehabilitation are shown in Figures 8 and 9.

In zones with increased leakage, calcification and pronounced mineral deposits are observed. Laboratory testing of concrete core samples obtained during geotechnical investigations indicates that the concrete remains in generally satisfactory condition, with compressive strength values ranging from 29 MPa to 45 MPa [15]. According to archival design documentation, the original specified concrete grade was MB20 [8].

Table 2 presents the maximum internal effects in the tunnel lining, including normal forces and bending moments before and after rehabilitation, together with the required reinforcement determined in accordance with Eurocode 2 (EC2).

In the structural components of the left tunnel tube the analysis covers the invert, sidewalls, and crown. The results indicate that after rehabilitation, a more favourable redistribution of internal forces is achieved in the invert and sidewall regions, while the crown section exhibits modified bending moment distribution due to the applied strengthening measures.

Variations in lining thickness (60–80 cm) observed in the sidewalls in both initial and rehabilitated states are attributed to construction tolerances and/or local degradation at the interface between the lining and the surrounding ground.

Table 2: Internal forces in tunnel lining before and after rehabilitation (design of required reinforcement determined in accordance with Eurocode 2 (EC2)

Structural element	N (kN)	M (kNm)	N_{ed} (kN) γ=1.35	M_{ed} (kNm) γ=1.35	Concrete class	Thickness	A_s (cm^2)
Invert	-683,0	-455,6	-992,0	- 615,0	C30/37	100 cm	1,98
Sidewall B	-1268,6	175,32	-1713,00	236,7	C30/37	60 cm 80 cm	0,00
Sidewall A	-1238,8	193,5	-1672,0	261,0	C30/37	60 cm 80 cm	0,00
Crown B	-460,0	-148,0	-621,00	-200	C30/37	45 cm 60 cm	4,64 1,17
Crown A	-1003	-143,00	-1354	-193,00	C30/37	45 cm 60 cm	0,00 0,00
Crown SL	-135,00	-0,39	-182	-0,53	C30/37	10 cm	0,00 0,00

Note: B – before the intervention, A – after the intervention, SL – shotcrete layer

6. CONCLUSIONS

The study demonstrates that the combined application of steel fibre-reinforced shotcrete (SFRS) and spray-applied waterproofing systems provides an effective rehabilitation strategy for existing railway tunnel linings.

Replacement of a 10 cm layer of the existing lining with SFRS results in stress redistribution and improved structural performance, enabling the system to resist tensile stress without the need for additional conventional reinforcement. Load-bearing capacity criteria are satisfied, with increased compressive forces and while bending moments remain approximately unchanged, leading to a more favorable stress state, particularly in the upper lining zone.

The integration of waterproofing systems significantly improves hydraulic performance by reducing water ingress and enhancing long-term durability. Mineral additives further contribute to impermeability through crystallization processes that reduce pore connectivity in the presence of moisture.

Overall, the combined use of SFRS and waterproofing systems represents a technically efficient and durable rehabilitation solution for ageing tunnel infrastructure, improving structural capacity, watertightness, and long-term service performance under combined mechanical and hydraulic loading conditions.

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