Numerical study on behavior of thin spray-on liner implemented tunnel lining

Chulho Lee, Soo-Ho Chang, Soon-Wook Choi & Tae-Ho Kang
Geotechnical Engineering Research Institute, Korea Institute of Civil Engineering and Building Technology, Korea

Kicheol Lee & Dongwook Kim
Department of Civil and Environment Engineering, Incheon National University, Korea

Byungkwan Park
Department of Geo-space, University of Science & Technology, Korea

ABSTRACT: A thin spry-on liner (TSL) has a higher initial strength, faster construction and higher waterproofing performance than the conventional sprayed concrete layer. TSL mainly consists of polymers that have much higher interface adhesion and tensile strength compared with the conventional materials. Despite of the outstanding advantages of TSL, it has not been used or implemented widely in construction sites. In this study, material properties and interface parameters of TSL were evaluated based on the results of laboratory experiments and numerical study. Because the contact behavior of TSL at the interface on concrete is important to understand the supporting mechanism of TSL from tunnel lining implementation, combination of cohesive and damage models was adapted at the interface between TLS and concrete lining in the numerical analysis. From the numerical analysis and laboratory test results, a design method of TSL implementation for the supporting underground structure was proposed.

Keywords: Thin spray-on liner, Ground improvement, Contact behavior, Numerical analysis, Interface parameter

1 INTRODUCTION

Thin Spray-on Liner (TSL) has high cohesion, initial strength, and workability and can be used as a waterproof material (ITAtech, 2013). In addition, TSL can be strongly adhered to concrete or concrete lining and can function as a complex structure with the attached concrete (Holter, 2016). The thickness of TSL is within a range of 3 ~ 5mm and the maximum thickness is typically less than 10mm. Therefore, the use of TSL can reduce the concrete lining thickness forming composite construction (EFNARC, 2008). In this study, physical and contact properties of TSL were analyzed through numerical analysis and experiments. After each analysis, the stability of the tunnel structure was assessed by implementing TSL on the concrete lining section of the tunnel structure. The stability of the tunnel structure was evaluated based on the permissible values of flexural compressive stress, flexural tensile stress, and shear force. The use of TSL on concrete lining results in reduction of concrete lining thickness based on the numerically analysis results.

2 CONTACT MODEL

To numerically analyze the contact behavior of TSL, it is necessary to evaluate contact characteristics of TSL. Contact properties of TLS on concrete are therefore essential for structural stability analyses of TLS implemented concrete lining. Reasonable cohesive contact model between concrete and TLS should be selected to simulate strong cohesive behavior of the TSL. Cohesive behavior in numerical analysis is defined as a part of the surface interaction properties and cohesive elements. The similarities include the linear elastic traction–separation model, damage initiation criteria, and damage evolution laws (SIMULIA, 2014).

2.1 *Linear elastic traction–separation behavior*

The traction–separation model is related to initial linear elastic behavior according to the initiation of damage and evolution energy. The elastic behavior can also be expressed by an elastic constitutive matrix as the normal and shear stresses when normal and shear separations occur at an interface

2.2 *Damage model*

Damage can be modeled by simulating the degradation and failure of the bond between two cohesive surfaces. The failure mechanism consists of two parts: A damage initiation criterion and a damage evolution law. If the damage initiation criterion is specified without a corresponding damage evolution model, there is no effect on the response of the cohesive surfaces. Damage during the traction–separation response for cohesive surfaces is specified in the same general way as for conventional materials, except the damage behavior is specified as part of the interaction properties of the surfaces. Cohesive surfaces can have only one damage initiation criterion and one damage evolution law; therefore, multiple damage mechanisms are not available.

2.3 *Damage evolution energy*

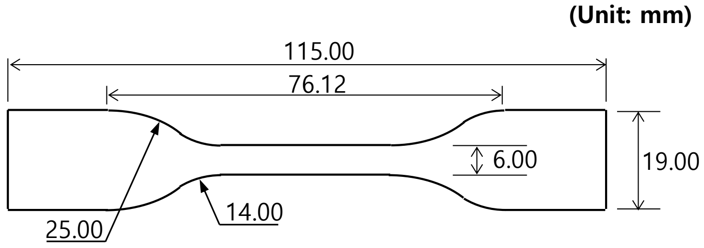
Damage evolution is the energy dissipated as a result of the damage (also known as fracture energy) and is equal to the area under the traction–separation curve. This energy is a property of the cohesive contact and can show linear or exponential softening behavior. The quantity is related to the effective separation at complete failure relative to that at damage. A linear or exponential softening law is selected to define the evolution in detail

3 MECHANICAL PROPERTIES OF TSL

3.1 *Material properties*

To evaluate the material properties of the TSL, tensile tests were conducted according to ASTM-D638 standards (ASTM, 2010). The specimen of TSL [plane view in Figure 1(a)] is made following the Type-4 from the ASTM standards with its thickness of 3 mm. Separately, three dimensional (3D) analytical modeling [see Figure 1(b)] was implemented using ABAQUS (SIMULIA, 2014) following the size of the actual specimen. Comparison of the numerical and experiment results of tensile tests allows selection of an appropriate constitutive model with their optimal parameters. A plastic model of TLS material was selected and used in numerical analysis effectively to reflect the actual tensile behavior of the TSL membrane. Holter (2016) also mentioned that the polymer-based waterproof membrane showed almost perfect plastic behavior.

The plastic model parameters include elastic modulus, plastic parameter values, and Poisson’s ratio. These parameter values are summarized in Table 1. The density of the membrane was obtained from direct measurement of the tested TSL specimen and the other values (elastic modulus and Poisson’s ratio) are determined from comparison of results from experiment and numerical analyses.



(a)

(b)

Figure 1. Thin spray-on liner (TSL) specimen: (a) Dimension of plane view and (b) numerical model

Table 1. Material properties of TSL

Material property	Value
Density (kg/m^3)	1,070
Elastic modulus (MPa)	434.41
Poisson's ratio	0.3

3.2 *Contact properties*

TSL is a material with strong cohesive force, which bonding stress on concrete lining is significant. To evaluate contact condition between the TSL and the concrete lining, the linear block support test proposed by EFNARC (2008) was performed. Dimensions of blocks and TSL of the linear block support test is shown in Figure 2. Load is applies to the middle block to induce adhesion failure between the blocks and TLS layer. TSL layer attached to the side blocks was fixed wit bolts.

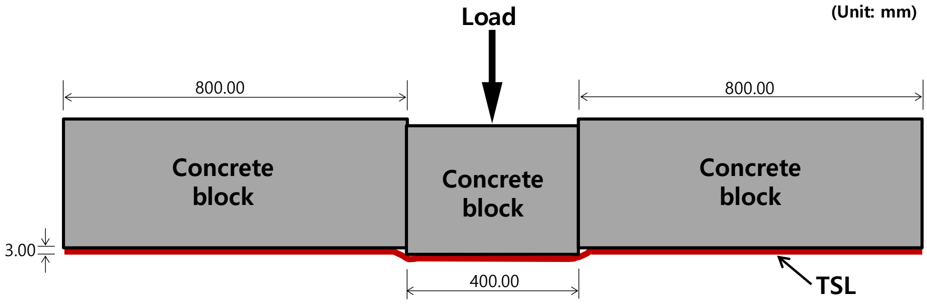


Figure 2. Plane view of linear block support test proposed by EFNARC (2008) with block thickness and TSL width of 40 mm.

For the numerical analysis (Figure 3), "cohesive behavior" model (SIMULIA, 2014) was used to simulate the contact behavior of the TSL and "damage" model (SIMULIA, 2014) was used to represent separation of the contact surfaces. The use of these two models is preferred to simulate contact-separation behavior between stiff and relatively extensible material compared with the commonly-used 'hard contact' model. The "cohesive model" is defined the traction (resistance)-separation (separation of contact surface) relationships. In this study, "cohesive stiffness" is defined to be equal to the equilibrium behavior. In the "damage" model, the maximum nominal stress at damage initiation and the fracturing energy (energy at occurring separation) were compared with the actual linear block support test values.

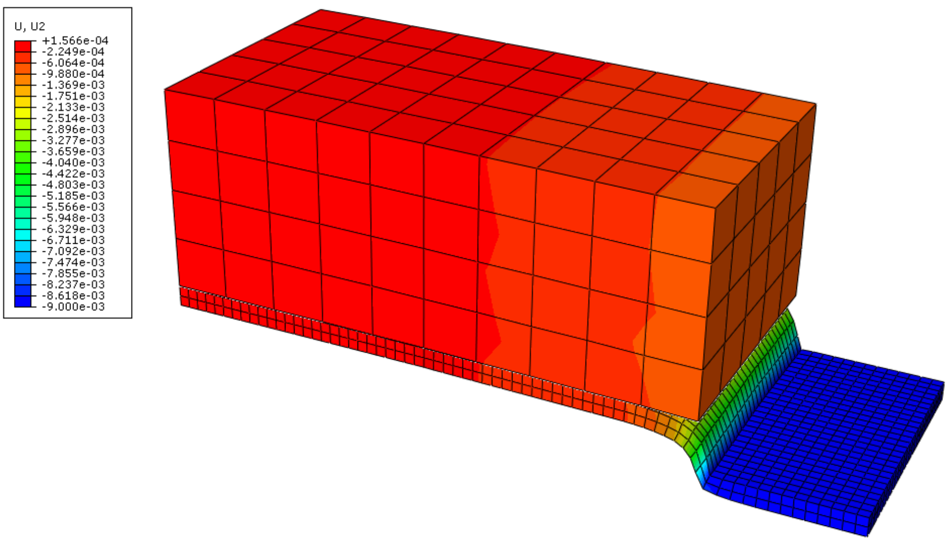


Figure 3. Visualization of the uniform vertical displacement of a TSL from numerical analysis

Table 2 shows the contact characteristics of TSL derived from the comparison results between experiment and numerical analysis. Cohesive stiffness of TSL influences the initial slope of the load-displacement relationship. It was found that the maximum nominal stress at damage initiation has an effect on the maximum load at the point of occurrence of the damage.

Table 2. Contact properties of TSL

Contact property	Value
Cohesive stiffness	0.25 GPa
Maximum nominal stress at damage initiation	0.75 MPa
Fracturing energy	2,200 J/m^2

4 IMPLEMENTATION OF TSL AT TUNNEL CONCRETE LINING

4.1 *Stability of concrete lining*

Generally, the concrete lining should be designed with sufficient stability and durability within its service life in consideration of the ground condition around the tunnel and the supporting ability (Midas, 2013). The cross section of tunnel is determined by allowable stress design method under the assumption of non-reinforced concrete lining. However, if load exceeds the allowable stress of concrete lining, strength-based design method is applied on concrete lining with reinforcement. The allowable stress design checks the allowable flexural compressive stress (f_{ca}), allowable flexural tensile stress (f_{ta}), and allowable shear stress (V_{ca}). The f_{ca}, f_{ta}, and V_{ca} were calculated using Equations (1), (2), and (3).

$$f_{ca} = 0.4 f_{ck} \tag{1}$$

$$f_{ta} = 0.13\sqrt{f_{ck}} \tag{2}$$

$$V_{ca} = 0.08\sqrt{f_{ck}} \tag{3}$$

where f_{ck} is material strength (in MPa) of concrete.

4.2 *Process of numerical analysis*

In this study, stability analysis was carried out for a low-level tunnel in which the surrounding ground is composed of rock grade V. Rock grade is determined based on evaluation sheep of Rock Mas Rating (RMR) system. Rock grade V corresponding to the most unfavorable rock grade, which requires much reinforcement prior to concrete lining installation. The shape of the concrete lining was designed as an arched shape by combining the dips and straight lines. It is preferable that circles, arcs and straight lines have a common tangent at connection points in order to smoothly form an arch (KR, 2014).

Therefore, the tunnel lining assumed in this study is composed of 2 circles in consideration of simplicity of analysis and contact area of TSL. Two-dimensional (2D) modeling was performed with the following tunnel geometry (Figure 4). The radius of top is 6.75 m, and the radius of the side wall is 4.66 m. The concrete lining was set to deformable-wire to calculate the axial and shear force of the beam using ABAQUS.

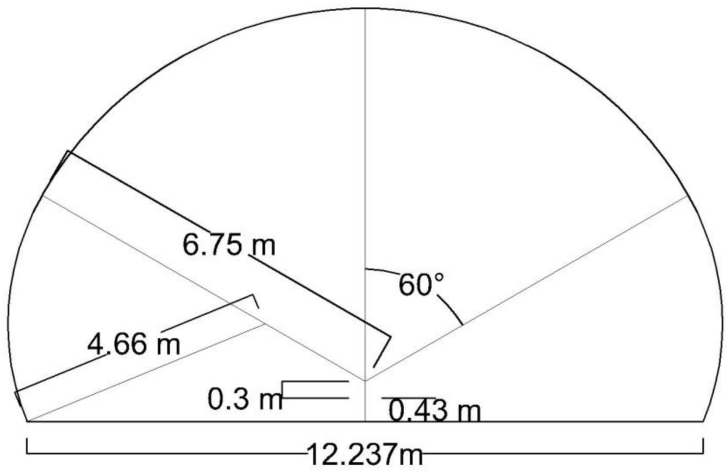


Figure 4. Modeling of tunnel lining (unit of lengths is mm)

Material characteristics of concrete lining in numerical analysis are assumed to be unreinforced concrete. In the case of plain concrete, the section of lining is designed following the allowable stress design method, and it is common to assume its behavior as linear elastic. The properties of the concrete lining are summarized in Table 3. The unit weight of ordinary plain concrete is 23.5 kN/m^3 and the material strength (f_{ck}) is 24 MPa. The elastic modulus is calculated according to the concrete structure standard (MOLIT, 2012).

Table 3. Material properties of plain concrete (Ahn, 2011)

Material	Density (kN/m^3)	Elastic modulus (GPa)	Poisson's ratio
Plain concrete	23.5	25.8	0.2

As the concrete lining is unreinforced, the allowable stress design method is used. It is appropriate to set the load combination to Case VI (load factor of 1) according to coefficients of load combination (MOLIT, 2012). Therefore, the working load should take into account gravity, rock load (normal and tangential) and residual water pressure. The calculated working loads are summared in Table 4.

Table 4. Acceleration and load acting on tunnel lining

Load	Gravity (m/s^2)	Stress from Rock on Lining (kN/m^2)		Residual water pressure (kN/m^2)
		Normal	Tangential	
Value	9.81	211.03	105.517	37.4

Figure 5 shows that the TSL layer is attached to the inner wall of the concrete lining. Three different thicknesses (3 mm, 5 mm, and 7 mm) of the TSLs are assumed. For the combined structure of TSL layer with concrete lining, the stresses of the concrete lining were evaluated under the given load conditions. Then, the "node-to-surface" contact method is used because "surface-to-surface" is not applicable for the contact between Shell (TSL) and Wire (concrete).

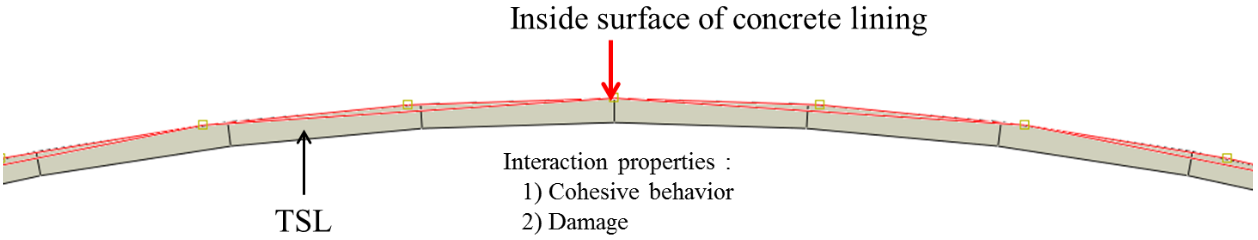


Figure 5. Interaction between TSL and concrete lining

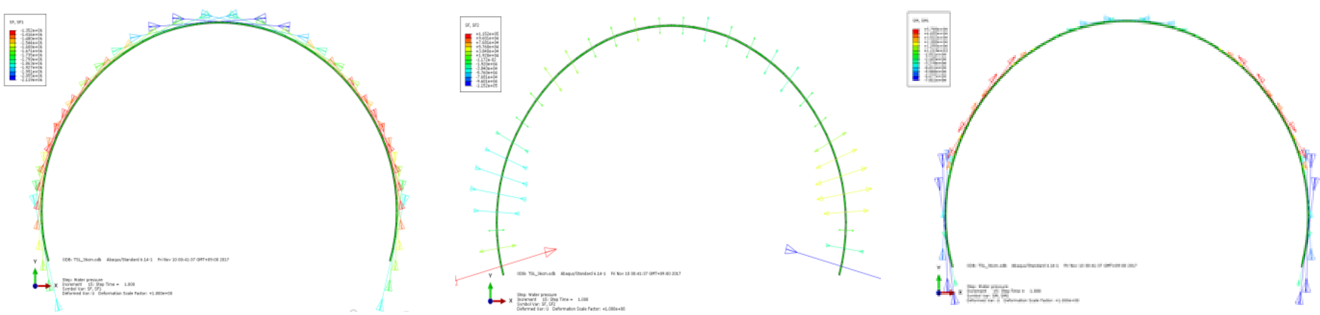
5 RESULTS OF NUMERICAL ANALYSIS

The flexural compressive stress, flexural tensile stress, and shear stress were calculated using Equations (4) and (5) by calculating the forces of each element of the member. The forces of each element of the member are shown in Figure 6 and forces are (a) axial load, (b) shear load and (c) moment.
The flexural compressive stress (f_c) and flexural tensile stress (f_t) can be calculated from Equation (4). It means flexural compressive stress when M / Z is (+) and flexural tensile stress when M / Z is (-). Equation (5) is a method of calculating shear stress (V_c).

$$f_c \ or \ f_t = P / A \pm M / Z \tag{4}$$

$$V_c = V / A \tag{5}$$

where, *P* is axial load, *A* is section area, *M* is moment, *Z* is section modulus and *V* is shear force.



(a) (b) (c)

Figure 6. The forces of each element of the member: (a) Axial load, (b) shear load, and (c) moment

The analysis results of resulting forces, moments and displacements are summarized in Table 5 which the difference of analysis result of concrete lining reinforced TSL and without reinforcement of TSL. The axial force, shear force, moment, and displacement variation according to the thickness of TSL show low differences. The axial force tended to increase with thicker TSL. However, shear force, moment, and displacement variation tended to decrease. The remaining factors did not have a large value compared to the axial force. Therefore, it can be seen that when the TSL is reinforced in the concrete lining, it has the greatest influence on the axial force acting in the cross direction.

Table 5. Differences between non reinforced concrete lining and reinforced by TSL

Thickness of TSL (mm)	Max. axial force (N)	Max. shear force (N)	Max. moment along the lining (Nm)	Lateral displacement (mm)	Vertical displacement (mm)
3 mm	220.0	-16.0	-4.2	0.0	-0.001
5 mm	370.0	-31.0	-7.0	0.0	-0.001
7 mm	520.0	-44.0	-9.8	0.0	-0.001

As a result, the effect of TSL thickness on concrete lining behavior under the allowable stress design method was not clear. This is considered to be due to the reinforcing effect of TSL contributing to the material. Lee et al. (2017) introduced the concept of toughness in the three-point bending strength test of concrete with TSL and explained it as energy form after destruction of the sample. The energy increased by about 10.1% compared to the case without TSL, which is the difference in plastic behavior after sample failure. That is, there was no difference in the contact of TSL in the elastic section (initial slope), but in the plastic section, when TSL was attached, a larger stress appeared. On the basis of this, TSL does not have a great influence on the elastic section of contacted the material, and reinforcement effect occurs in the plastic section after yielding of the material.

6 CONCLUTION

Physical properties and contact properties of TSL were assessed based on the numerical analysis using ABAQUS and the linear block support test results. After each analysis, the stability of the TSL implemented tunnel lining was analyzed. The method of analysis of the tunnel follows the allowable stress design method. The stability analysis results of tunnel concrete lining with TSL are summarized as follows:

1. When TSL was applied, the axial force tended to increase with thicker TSL, but the shear force and moment tended to decrease. However, the reinforcement effect of TSL was insignificant
2. The allowable stress design of tunnel lining considered in this study assumes that the concrete lining is linear elastic. However, TSL does not contribute much to the elastic section of the TSL reinforced material, and it plays a role in increasing the plastic strength after the elastic section. Therefore, in order to understand the reinforcement effect of TSL, it is appropriate to analyze the design method considering the plasticity state such as plasticity design method rather than allowable stress design method.
3. The TSL implementation on tunnel concrete lining functions as additional tunnel supporting material based on the numerical analysis results. As the favorable TSL functions are proven only from numerical analyses, future verification should be conducted by analyzing the behavior of TSL implemented concrete lining from detailed experiments or field test results.

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