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Numerical approach to assessing the contact characteristics of a polymer-based waterproof membrane

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ABSTRACT

A waterproof membrane sprayed onto concrete enables faster construction compared with a conventional sheet membrane. The sprayed raw material, which is polymer mixed with water, becomes completely continuous waterproof thin membrane after a certain curing time. Such membranes have not been widely used in East Asia due to less confidence of their performance and limited applications despite of their outstanding structural properties and many projects in Europe, especially in the UK (at least 6 projects), which include higher cohesion at the interface and higher tensile strength. This study evaluates the material and contact properties of a waterproof membrane based on the results from laboratory experiments and numerical analyses. Interface properties of the waterproof membrane were calibrated from results of the linear block-support test proposed by European Federation of National Associations Representing for Concrete (EFNARC). A numerical model for simulating three-point bending tests was then developed and used to examine structural effects of the membrane. In results of numerical analysis, the contact conditions between the lining and the membrane had little effect in elastic behaviors, but tensile behavior of concrete lining had a relatively large effect.

1. Introduction

Waterproofing is one of the main components to be checked to maintain structural safety and serviceability. Groundwater is an important consideration in engineering projects because it can weaken and degrade a structure causing subsidence near an excavated section (Nakashima et al., 2015). Excessive leaking can increase construction costs, delay construction, and suspend the operation of structures (ITAtech, 2013). To waterproof underground structures, especially tunnels, sheets and drainage are generally used, but they can develop leaks sufficient to suspend operation. Therefore, an economical and effective way of waterproofing should be investigated.

EFNARC (2008) and ITAtech (2013) proposed the use of sprayed waterproof membranes (sheets) and thin spray-on liners (TSLs) for tunnels and underground structures. The sprayed waterproof membranes and TSLs prevent water or moisture penetrates into lining structure. Sprayed polymer membranes are quick to deploy and have better construction time than conventional sheets. TSLs have a similar composition to waterproof membranes, but TSLs were mainly used as a supporting material along with a shotcrete primary lining (Holter, 2015). The sprayed raw material (generally mixture of polymer and water) reacts to become a continuous waterproof membrane after a certain curing time. Both materials have the similar purpose and performances, but there is a difference in material composition.

A sprayed waterproof membrane is commonly 3–5 mm thick, with a maximum thickness of less than 10 mm, which is thin compared with shotcrete (EFNARC, 2008). A sprayed waterproof membrane also has the following advantages: (1) it is quicker to install than sheet membrane, (2) it may replace shotcrete and wire mesh used in the blasted tunnel to prevent from rock-falling with providing high initial stability and tensile strength, and (3) it has excellent waterproofing performance, which can prevent groundwater inflow and can reinforce the rock mass.

The most obvious way to assess the performance of a sprayed waterproof membrane is to perform field and laboratory-scale tests (Tannant, 2001). However, a few test results on the interface properties of sprayed waterproof membranes have been reported (Verani and Aldrian, 2010; Holter, 2015; Johnson et al., 2016; Su and Bloodworth,

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2016, 2018). A sprayed waterproof membrane must adhere to its supporting wall by cohesive and tensile strengths, because it is generally constructed between the primary and secondary linings in a tunnel (Su and Bloodworth, 2016). It can thus support and reinforce an underground structure, and may possibly reduce the required thickness of the secondary lining, reinforcement ratio, or concrete grade. Nakashima et al. (2015) reported that layered structure of a sprayed waterproof membrane installed between two shotcrete layers behaves as an integrated solid beam. However, further research on the effect of membrane on load sharing amount of the integrated solid beam was recently reported (Su and Bloodworth, 2018). Therefore, it is important to understand the physical material properties of these membranes and the lining-to-membrane interface behavior.

Holter (2015) investigated the use of an EVA-based membrane for Sprayed Concrete Lining (SCL) in hard rock using a direct shear test for various samples, noting increasing strain softening behavior and bilinear behavior of the membrane with almost perfect plasticity. Johnson et al. (2016) reported the structural properties of a sprayed waterproof membrane, and derived its range of quasi-elastic behavior given a useful degree of composite action. Chang et al. (2015) reported shear strength, uniaxial compressive strength, and bearing capacity [as presented by EFNARC (2008))] for two TSL samples made with different mixing methods and compositions. They also reported an enhancement of properties upon application of a TSL. In a numerical analysis of shotcrete failure in tunnels, Shin et al. (2009) considered the cohesion of shotcrete as an important factor influencing tunnel support capacity. This study evaluates combined behavior of sprayed waterproof membranes attached to concrete lining based on the results of laboratory tensile tests and numerical analyses following the linear block-support (LBS) test proposed by EFNARC (2008).

In this study, the membrane properties and interface properties were obtained from experiments and numerical method instead of the commonly used "composite beam" approach and numerically simulated both pre- and post-interface debonding stage. Then the structural effects of a sprayed waterproof membrane on concrete lining were analyzed. The membrane's reinforcing effects of the concrete lining were evaluated based on the results of numerical analyses simulating three-point bending tests varying conditions (material properties, maximum stress of damage initiation, cohesive stiffness, fracturing energy, softening effects) and their results are discussed.

Firstly, the numerical approaches for simulating the behavior of membrane itself and the membrane-concrete interface are presented. The properties of the material itself were determined by tensile test and the interface characteristics were determined by LBS (Linear Block-Support) test. After determining material and interface characteristics of sprayed waterproof membrane, the performance of composite lining with sandwiched sprayed waterproofing membrane using calibrated material and interface properties was investigated numerically and the results are compared with concrete linings without membrane.

2. Theoretical background

To analyze the contact behavior of spray applied waterproofing membrane using numerical analysis, it is necessary to evaluate proper contact characteristics of spray applied waterproofing membrane. Contact properties are therefore essential for structural stability analyses. Bonding with the rock mass is particularly important for polymer-type supports (Maidl et al., 2013). Reasonable cohesive contact model should be selected to simulate strong cohesive behavior of the sprayed membrane.

Cohesive behavior in numerical analysis is defined as parts of the surface interaction properties and cohesive elements. The governing equations of cohesive surface behavior are similar to those of cohesive elements with traction–separation constitutive behavior. The similarities include the linear elastic traction–separation model, damage initiation criteria, and damage evolution laws (SIMULIA, 2014).

However, damage in surface-based cohesive behavior is related to an interaction property, not a material property. Within the framework of strain and displacement, cohesive elements are reinterpreted as contact separations, which are the relative displacements in the contact-normal and shear directions between the nodes on the slave and master surfaces. In contrast, stresses of a surface-based cohesive model are related to cohesive forces acting in the contact-normal and shear directions between the surfaces.

2.1. Linear elastic traction–separation behavior between interfaces

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 strain when normal and shear separations occur at an interface. The elastic behavior can be written as follows:

$$t = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} k_{nn} & k_{ns} & k_{nt} \\ k_{ns} & k_{ss} & k_{st} \\ k_{nt} & k_{st} & k_{tt} \end{bmatrix} \begin{Bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_t \end{Bmatrix} = K\varepsilon \tag{1}$$

where $\boldsymbol{t}$ is a nominal traction stress vector that consist of three components (applied to three-dimensional problems), K is the shear stiffness matrix and ε is a nominal strain. The t_n, t_s and t_t represent the nominal tractions in the normal and the two local shear directions, ε_n, ε_s and ε_t are the corresponding nominal strains.

2.2. Interface 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. Fig. 1 shows a typical traction–separation failure mechanism. 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 cannot occur simultaneously.

Damage initiation refers to the beginning of degradation of the cohesive response at a contact surface. Degradation begins when the contact stress reaches a specified damage initiation criterion. The terms of t_n^0, t_s^0, and t_t^0 in Fig. 1 represent the peak values of contact stress for separation perpendicular to the contact surface or in the shear direction. Likewise, δ_n^0, δ_t^0, and δ_s^0 represent the peak values of contact

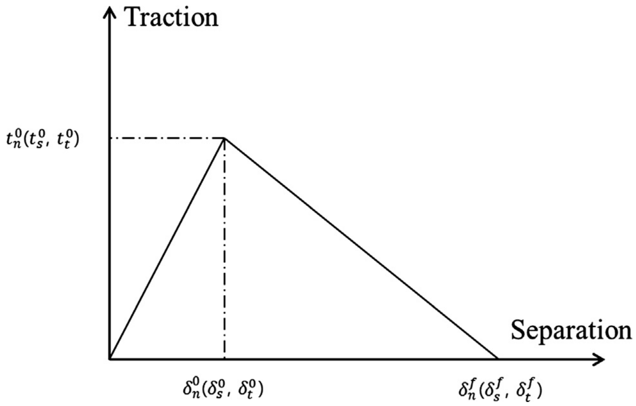

Fig. 1. Typical traction–separation response (modified after SIMULIA, 2014).