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Numerical Study on Structural Behavior of Arched Shotcrete Liner Reinforced with Steel Supports

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Abstract: This study aims for analyzing the structural responses of the shotcrete liner reinforced with several different type of steel supports. Effects of the different type of steel supports (bar reinforcements and H-shape supports) on the shotcrete liner are numerically investigated beyond its peak load capacity. To simulate nonlinear composite behaviors of the shotcrete-steel support, a fiber section element modelis used.The numerical load-displacement response is compared with previous experimental data on the shotcrete lining without reinforcements to validate the numerical model. Several parametric studies on the performance of the composite support are also conducted to obtain some clues related to the optimized steel type.

Keywords: shotcrete, steel reinforcements,composite,fiber section element, nonlinear analysis,NATM

I. INTRODUCTION

The new Austrian tunneling method (NATM) is one of the tunnel construction methods and has been used all over the world. After tunnels are excavated, tunnel supports such as shotcrete, rock bolts, and so on, are installed to satisfy a new state of equilibrium in the ground. In particular, shotcrete lining is often reinforced by steel supports in tunnel portals or in adverse ground conditions where an arch effect is not developed. Reinforcing steel supports improvethe performance of shotcrete linings and to ensure the stability of tunnel.Currently, H-shaped steel ribs and lattice girders have been widely used as steel supports in NATM tunneling. However, the installation of H-shaped steel ribs is not easy due to their heavy weight which results in workability problem. In addition, H-shaped steel ribs induce unexpected internal gaps between the shotcrete and the steel support after spraying shotcrete because of their geometric characteristics. Unexpected gaps may lead to problems with resisting the ground pressure. To overcome the problem, lattice girders were developed but they have lower stiffness and loadbearing capacity than those of H-shaped steel ribs. Moreover, the lattice girders frequently exhibit local failures at the joints of each bar (Kim et al., 2013a) [1].Reinforced ribs of shotcrete (RRS) are worthy of considering as an alternative steel support. It has been usually used in the Norwegian method of tunneling (NMT) as tunnel supports. It not only improves workability at construction but also reduces the internal gap by fully bonding with the shotcrete. In addition, it has the advantage of dealing with the change in cross-section of the tunnel and in ground pressure more easily than other standardized steel supports such as H-shaped steel ribs and lattice girders.

In general NATM tunnel design, the load capacity of steel supports is mostly ignored or regarded as a temporary support because of the following reasons: lack of verification on fully composite behavior of shotcrete and steel supports and efficient design process. However, this causes excessive design of the tunnel liner; steel supports have high load resistance capacity due to its superior compressive and flexural stiffness. Several researchers tried to consider the steel resistance in the liner design and to simulate composite behaviors of the shotcrete–steel composite liner. Hoek (1998) [2] examined types of steel supports that had been used in weak rock and checked the role of steel supports in terms of tunnelsupport systems by estimating the maximum support pressure for different support systems. Mashimo et al. (2002) [3]set up arched shotcrete specimens without steel reinforcement and tested the load capacity.They also conducted numerical analysis to estimate the load–displacement response of the shotcrete lining by using the fiber section element model. Hoek et al. (2008) [4] described the methods that can be used to optimize the design of tunnels using a combination of reinforcement and support methods. Particular attention was given to tunnels in very weak rock or soil for which large deformations could occur. Carranza-Torres and Diederichs (2009) [5] described a methodology for the mechanical analysis of composite supports, such as liners consisting of shotcrete and steel supports. The method was based on the equivalent cross-section approach and included a frame analysis for circular and elliptical tunnels by using the properties of equivalent cross-sections. Kim et al. (2013) [6] conducted nonlinear analyses of the shotcrete–steel composite beam by using the fiber section element model. Although the model represented nonlinear composite behaviors of the shotcrete-steel support, effects of the combination of axial and bending forces were not included.

The above previous studies provided severalnumerical approaches for NATM tunnel design to represent the shotcrete reinforced with steel reinforcements. However, the axial and bending effects and nonlinear composite characteristics are not considered simultaneously. Effects of various support type on the load capacities of the shotcrete-steel supports are not closely investigated. It is necessary to examine these effects with respect to reasonable and economic design. For this reason, this study numerically analyzes the performance of the shotcrete reinforced with different types of steel supports by considering the axial-bending effects and nonlinear material behaviors. To verify the numerical model to simulate the arched shotcrete liner with steel support, numerical results of the shotcrete lining without steel supports are compared with experimental data of Mashimo et al. (2002). Furthermore, numerical analyses of the shotcrete liner are also conducted to investigate effects of several different types of steel supports.

II. MODEL DESCRIPTIONS

1. Fiber Section Element

The fiber section element is one of the beam element. Unlike general continuum based models, the element is proper to represent nonlinear composite behavior of structures with low computational cost. In the fiber section element, the beam cross-section is divided into a number of fibers with area. The constitutive relations of materials are defined in each fiber (Fig. 1). Fiber section elements used in this study are formulated based on the Euler–Bernoulli beam assumption; small deformation and plane cross-section which is normal to the longitudinal axisafter deformation. Detailed descriptions of the element, including the element formulation and analysis process, are presented in Spacone et al. (1996) [7].

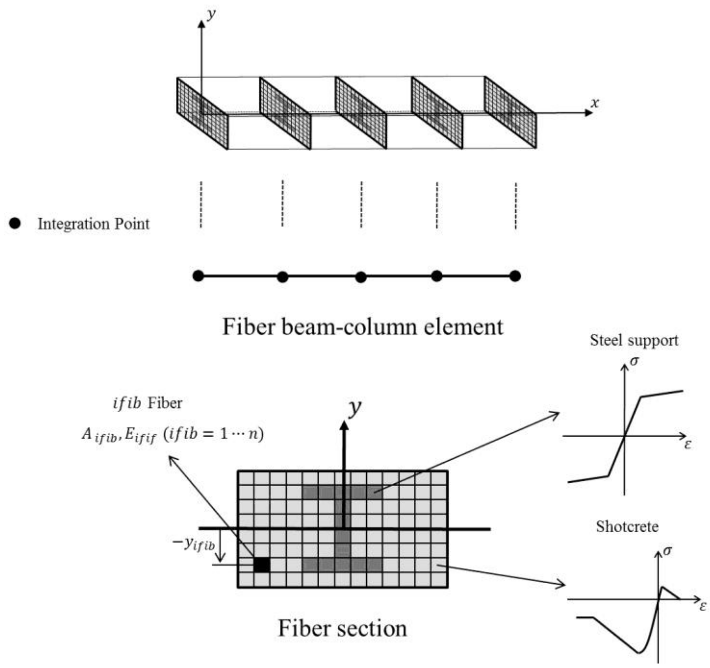


Figure 1 Scheme of fiber section element

2. Material Constitutive Relations

2.1.1 Shotcrete

Steel fibers are mostly added into the shotcrete to overcome the brittle behavior of shotcrete. The addition of steel fibers into shotcrete enhances of increasing the ductility and toughness. It'srequired to determine the constitutive equation and material properties for the equation considering the effect of steel fiber reinforcement in order to precisely reproduce the behavior of shotcrete liner. In this study, the Kent & Park model for compression and the linearsoftening model for tensionwere adopted for the stress-strain relation of steel fiber reinforced shotcrete (SFRS).The constitutive relation is depicted as shown in Fig. 2:

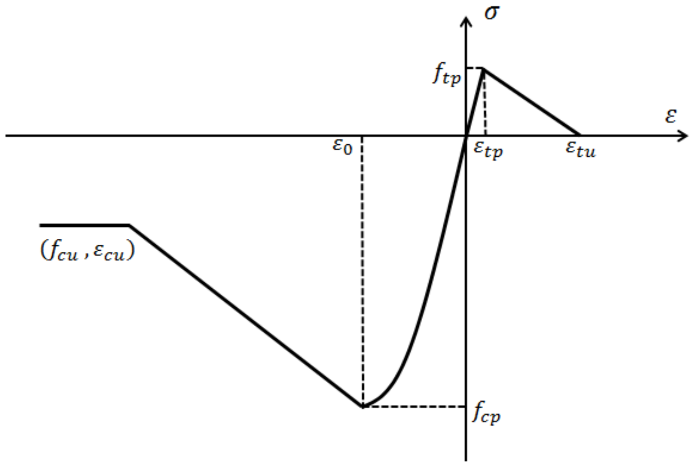


Figure 2 Stress-strain relation of shotcrete

where$f_{cp}$and$\varepsilon_0$respectively represent the compressive strength and the corresponding strain, $f_{cu}$and $\varepsilon_{cu}$are the crushing strength and the corresponding strain, respectively,$f_{tp}$is the tensile strength, and $\varepsilon_{tu}$is the ultimate tensile strain.Although this model is widely used for concrete, the model can be adopted to represent the shotcrete according to experimental results of Leung et al. (2005) [8] who compared mechanical characteristics of wet-mixed SFRS with those of steel fiber reinforced concrete (SFRC);they concluded that SFRS and SFRC are found to exhibit similar behavior. The compressive material properties of shotcrete can be more easily measured while the tensile material properties are not. For this reason, the tensile mechanical parameters of shotcrete are determined by an inverse analysis method used in the study of Elsaigh et al. (2002) [9].

2.1.2Steel

The constitutive material model of steel was defined as the linear isotropic hardening model (Fig. 3):

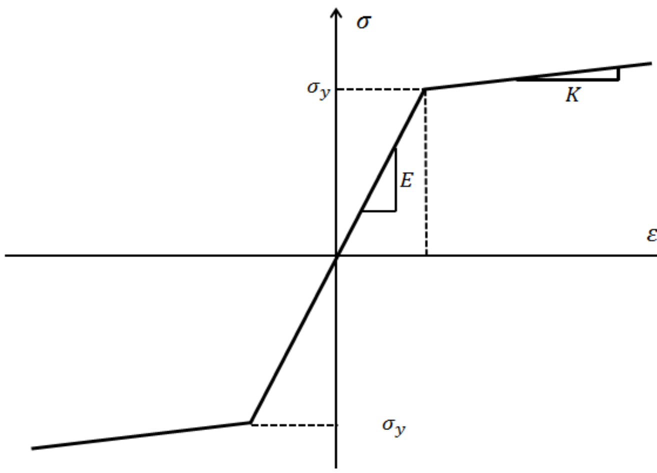


Figure 3 Stress-strain relation of steel

where*E*is the elastic modulus of steel supports, σ_y is the yield stress of steel supports, *K* is the strain hardening coefficient.

2.1.3Rock

To simulate rock–structure interaction analysis for a tunnel linings, a hyperbolic modelwas used for the reaction pressure–displacement relation of the rock;this model is good for reproducing nonlinear behaviors of the ground. Detailed descriptions of the hyperbolic model can be referred to Oreste (2007) [10].Because this model only considers strain hardening, the modified hyperbolic model is developed by introducing strain softening for post failure behavior of the rock mass as shown in Fig. 4. The strain softening is linearly defined; the softening initiates at the peak resistance and decreases to the residual resistance. Each notation in Fig. 4 is the following; P_{max}:maximum reaction pressure,P_{peak}:peak reaction pressure,P_{res}:residual reaction pressure, δ_{peak}:the corresponding displacement to the peak reaction,δ_{res}: displacementwhen the residual reaction starts, η_0: initial slope of the pressure-displacement curve.Because of difficulties in determining parameters related on softening behavior, assumptions used in Lee et al. (2007)were applied to determine these parameters [11]:$P_{res} = 0.6P_{peak}$ and$\delta_{res} = 1.5\delta_{peak}$; the relation was derived by comparing numerical results with field measurements at a tunnel construction site.

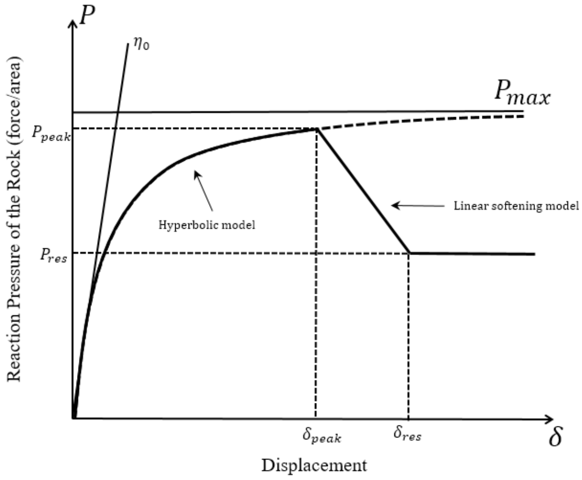
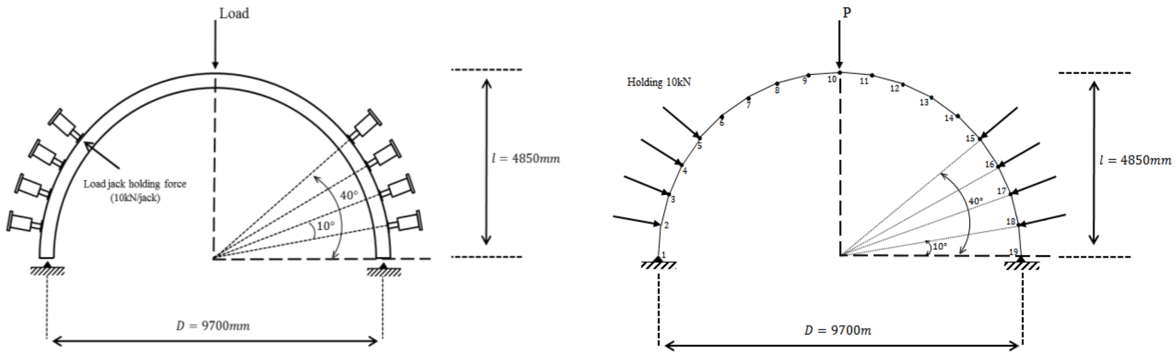


Figure 4 Modified hyperbolic equation for rock

III. MODEL VALIDATION

The present model of shotcrete–steel liner wassimulated and the results were compared with experimental results [2] for validation.The numerical model was implemented by OpenSees, which was developed by University of California to simulate the seismic response of structural and geotechnical systems. The experiment was carried out to evaluate load capacity of the arch-shaped shotcrete lining without steel supports; shotcrete was only reinforced with 0.8 × 60mm hooked end steel fibers whose volume fraction of steel fiber was 0.5%.The specimen was a semicircle with the outer diameter of 9700 mm, the width of 1000 mm, and the thickness of 300 mm. A load was applied at the crown in a displacement control manner after the axial force was acted with 8 jacks up to 10kN/jack. Each jack was placed in left and right bottom of specimen as shown in Fig. 5a.



(a) Arch-shaped loading test (b) Finite element model

Figure 5 Scheme of experiment and numerical model

A finite-element model was created under the identical conditions of the loading experiment for the shotcrete lining. The cross-section was divided into 4 fibers in width and 16 fibers in height. The arched specimen was modeled as 18 fiber section elements. The load was applied at the crown in a displacement-control manner after holding the jack forces of 10 kN at the left and right sides of the specimen. The loads and boundary conditions are shown in Fig. 5b. Input parameters for material constitutive models are listed in Table 1.

As shown in Fig. 6, the load–displacement response at the crown approximately agrees with experimental data. Thus, the present model can predict nonlinear behavior shotcrete support, including hardening and softening effects, and can be used to analyze behaviors of the shotcrete-steel support.

Table 1 Input parameters for material constitutive model of shotcrete

Kent-Park model (for compression)				Linear softening (for tension)	
f_{cp}(MPa)	ε_0	f_{cu}(MPa)	ε_{cu}	f_{tp}(MPa)	ε_{tu}
22	0.002	4.4	0.006	2.8	0.004

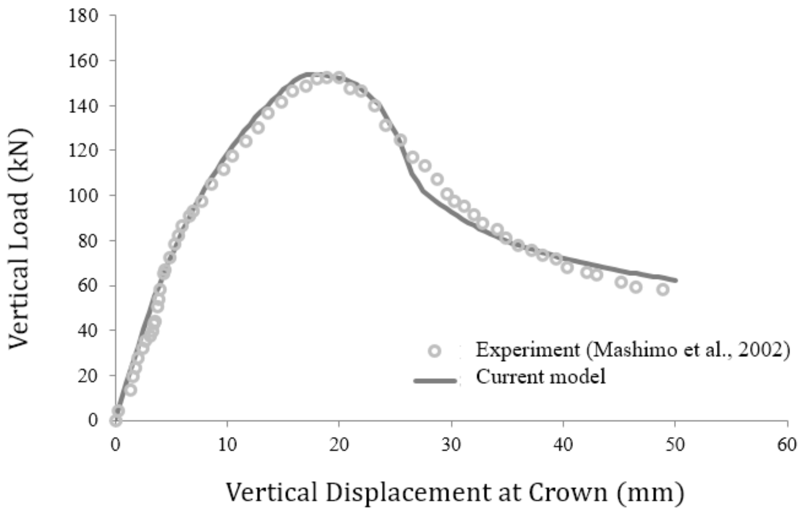
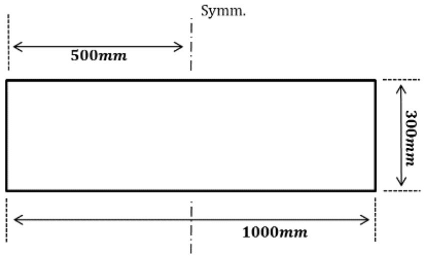


Figure 6 Comparison with experimental and numerical results

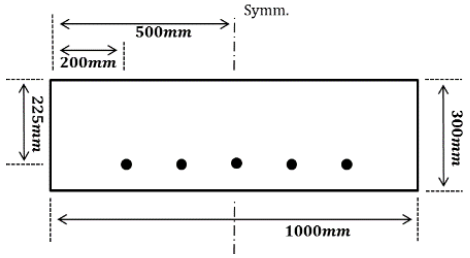
IV. ANALYSIS OF SHOTCRETE REINFORCED WITH STEEL SUPPORTS

Shotcrete liners reinforced with several type of steel reinforcements, of which the cross-section are as shown in Fig. 7,are numerically analyzed. The same finite element model was used, except replacing the jack forces with ground springs. Input parameters for springs are the following; P_{peak}: 67.2 kPa, δ_{peak} : 8 cm, P_{res}: 40.3 kPa, andδ_{peak} : 12 cm. All thecross-section is the width of 1000 mm and the height of 160 mm. H 150 x 150 x 10 x 7 (H shaped support type, SS400) and steel bar with the diameter of 19 mm (bar type, SD400) are used as steel supports, respectively. The number of steel bars is determined to have the similar area of flange of H-shaped steel ribs. Five steel reinforcement bars are used for the singly reinforced cross-section and ten steel reinforcement bars are used for the doubly reinforced one.For convenience, liners with each type of steel supports are named as the following in the paper; A: shotcrete only, B:singly reinforced bars, C: doubly reinforced bars, and D: H-shaped support.

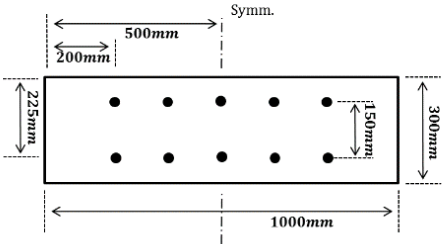
Although there were a tendency for load capacities in all of the types to decrease after the peak load, the shotcrete liner reinforced with steel supports show less reduction of the load capacitythan that of A (see Fig. 8).For the pre-peak region, similar load-displacement responses were shown, regardless of the type of steel support. However, beyond the peak load, the load-carrying capacities of C and D (208.46kN and 206.76kN, respectively) had tendencies to increase than A. On the other hand, the peak load of B showed that the maximum load capacity is 191.95kN which is higher than that of A by approximately 1.5%. This means that reinforcing the rebar at the bottom of the cross-section has no significant effect on improving the load-carrying capacity.Compared with the post-peak load–displacements values, it is found that the supporting effect of C is superior to other cross sections. On the other hand, D had rapid softening of the load-carrying capacity more than C immediately after peak load. In addition, the residual load of D approached that of B as the vertical displacement increased.



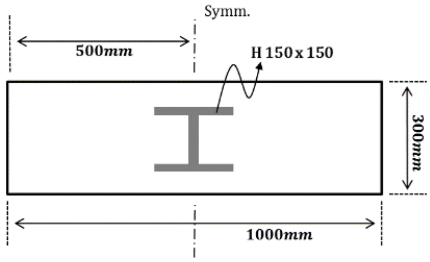
(a) No reinforcements: A



(b) Singly reinforcement bars: B



(c) Doubly reinforcement bars: C



(d) H-shaped beam: D

Figure 7 Cross-section of shotcrete liner

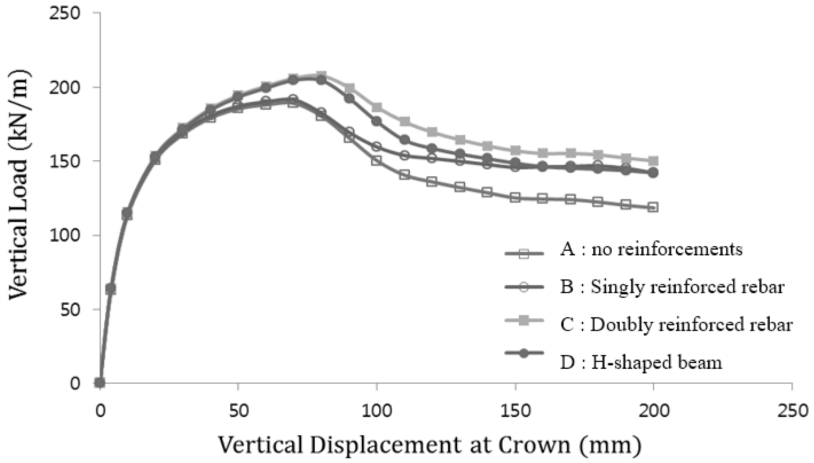


Figure 8 Load-displacement response of shotcrete liners with and without reinforcements

V. CONCLUSIONS

This study has performed various numerical analyses in order to evaluate the structural behaviors of shotcrete lining reinforced with several representative steel reinforcements. A numerical model for predicting the responses of the shotcrete–steel support were presented and validated.The supporting effect depending on configurations for steel reinforcements was also analyzed.

Based on the findings of this study, the following conclusions can be drawn.First of all, it is confirmed that the fiber section element can well predict the nonlinear behavior of shotcrete liner reflecting the axial and bending combination effect. It is also shown that the model can reproduce a simplified composite behaviors of shotcrete liner reinforced with steel supports. Considering the characteristics of the fiber section element,the application of the element would lead to efficient design and analysis by reducing computation cost. Furthermore, behaviors of the shotcrete lining based on the configuration of reinforcements show a significant difference. The maximum load-carrying capacity of the liner with doubly reinforced cross-section increases by 10.21% when compared with the liner without reinforcements. Beyond the peak load, all the cases could resist load softening. Among them, however, the doubly reinforced cross-section showsthe most supporting effects(in particular for the post-peak region) whilethe singly reinforced cross-section has almost no improvement. From the results of load-displacement curves, steel rebar type could be used as an alternative the previous steel reinforcement types such as H-shaped beam and lattice girder.

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