The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

A nonlinear analysis of the shotcrete lining reinforced by steel bars using fiber section model

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ABSTRACT

A numerical analysis of shotcrete lining reinforced by steel bars, instead of H-section beam and lattice girder commonly used as steel supports in NATM tunnel of Korea, is treated in this paper. The nonlinear analyses of reinforced shotcrete lining are performed by using fiber section model. A constitutive model based on analyzing the existing experimental studies of tensile behavior of steel fibre reinforced shotcrete is presented. The proposed constitutive model is applied to finite section models of steel fibre reinforced shotcrete lining with steel bar reinforcements. The steel bar reinforcements assumed an elastic and perfect plastic material. To validate whether the constitutive model and numerical results are reasonable, the load-displacement of numerical analysis are compared with results of 3 point flexural tests on beam with only steel fibre and double reinforcements. The numerical analyses examine the behavior of pre-peak and post-peak response of reinforced shotcrete. The numerical results show good agreements with the experimental results of each case.

1. INTRODUCTION

H-section beam type and lattice girder are widely used as the primary support of tunnels excavated by New Austrian Tunneling Method (NATM) in Korea. Although the application of these types of steel supports bring enhancement of long-term support capacity and ductile behavior on a shotcrete lining, there are difficulties that shotcrete is not sprayed to be packed fully in the rear of steel support and thickness of shotcrete lining excessively increase in cases of using H-type beam and lattice girder, respectively. These cause that loadings such as weights and seismic loads in the ground are not properly transferred to tunnel structure and an unexpected construction cost increases. For these reasons, the use of steel bars has emerged as an alternative of the existing primary supports in NATM tunnel. Recently, many researchers have studied shotcrete lining to consider the load capacities of steel reinforcements in it and its composite behavior. Park (2010) estimated experimentally the flexural load

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capacities of shotcrete reinforced with various steel sets such as H-type beam, steel bar, and lattice girder. They asserted it is possible to use steel bars as reinforcement of shotcrete lining instead of H-type beam or lattice girder, even though the shotcrete lining become more nonlinear and flexible.

In this study, fiber finite beam-column element formulation is introduced to estimate the nonlinear and composite behavior of shotcrete lining reinforced with steel bars. The constitutive model for shotcrete materials is developed to consider the tensile resistance of shotcrete, because of containing steel fiber in shotcrete matrix. To verify the proposed constitutive model and show the efficiency and accuracy, finite element models corresponding to the several existing flexural tests are created, and then its results are compared with each other.

2. NUMERICAL ANALYSIS

2.1 Constitutive model for steel fibre shotcrete

Because shotcrete tunnel lining usually contains steel fibre, it indicates ductile behavior after peak load and has residual tensile strength, unlike plain concrete. Several experimental studies on material properties of steel fibre reinforced shotcrete (SFRS) are carried out by Kim (2011), Leung (2003) and Seo (1986). These present that increase of compressional strength and stiffness by reinforcing steel fibre can be negligible. On the other hand, the tensile strength and its stress increases nearly linearly until the peak, then rapidly declines to residual strength, about 50~80% of the peak strength. Finally, tensile stress decreases linearly to zero. A residual strength of shotcrete is dependent on fiber length, volume fraction of fiber, strength test type.

Based on these results, a multi-linear uniaxial stress-strain relation for shotcrete in compression and tension as shown Fig.1, is adopted to simulate the behavior of SFRS.

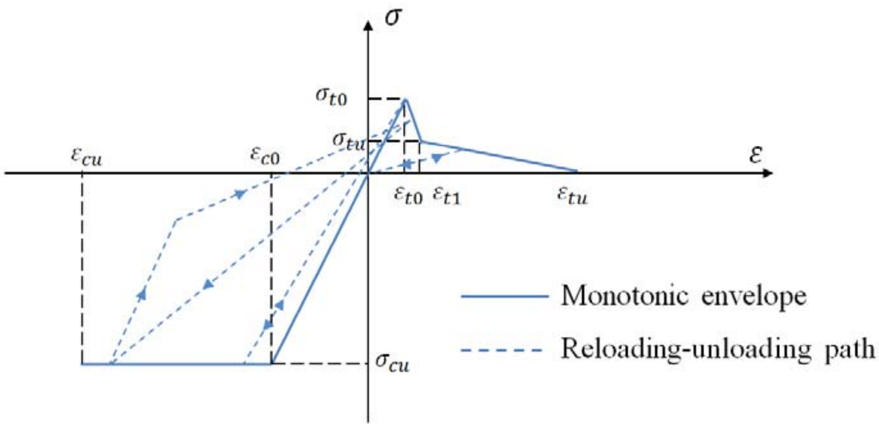

Fig. 1 Uniaxial constitutive model for steel fibre reinforced shotcrete

In Fig. 1, σ_{t0} and ε_{t0} represent the peak tensile strength of SFRS and the corresponding elastic strain respectively, σ_{tu} is the residual tensile strength, ε_{t1} is the corresponding strain to σ_{tu} , σ_{cu} is the compressive strength, ε_{c0} is the limit of elastic strain in compression, each of ε_{cu} and ε_{tu} is the ultimate strain in compression and tension. The hysteric unloading and reloading path follows the rule proposed by Yassin (1994), which is a set of linear stress-strain relations.

2.2 Finite section model

A fiber section model, has used in many studies to perform the nonlinear analysis of RC structures under cyclic loading, has several fiber section composed of bundles of fibers. Each fiber has a one dimensional nonlinear stress-strain relation. In this study Force-based beam-column elements are used for formulation, developed by Spacone (1996). The finite section models of two simply supported SFRS beams with different cross sections, corresponding to 3 point flexural tests carried out by Park (2010), are created by using fiber section as in Fig. 2. The proposed material constitutive relation and elastic-perfect plasticity model are used for SFRS and steel bars, respectively. The material properties assigned to each of them are indicated in Table 1.

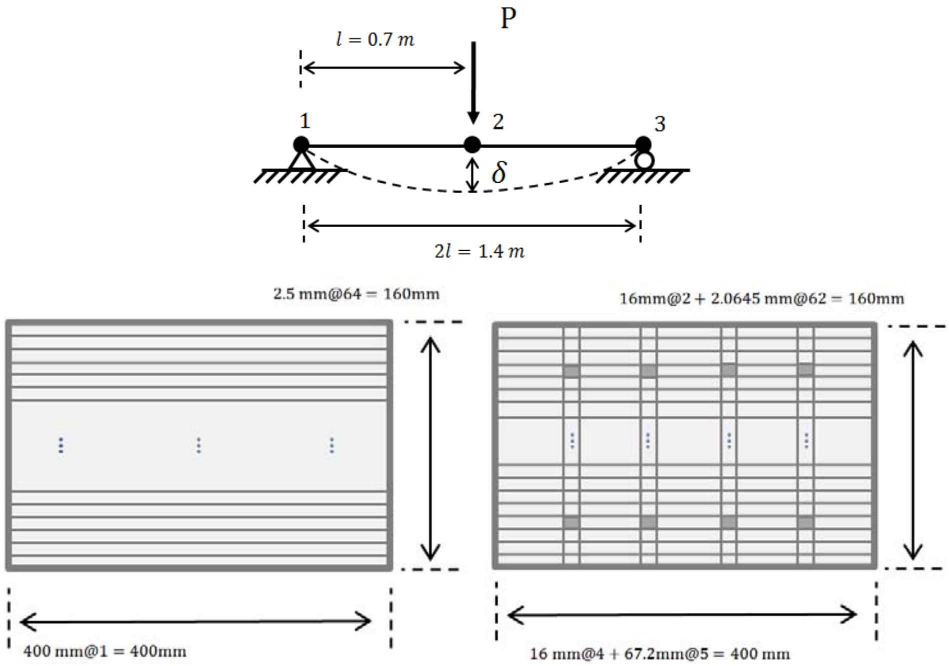

Fig. 2 Finite element model and fiber section

Table 1 Material properties assigned into shotcrete and steel bars

		E_0 (GPa)	σ_{cu} * (MPa)	ε_{cu} (m/m)	σ_{t0} (MPa)	σ_{tu} (MPa)	ε_{t1} (m/m)	ε_{tu} (m/m)
SFRS	Multi-linear model	12.561	-29.87	$-4x10^{-3}$	5	3.5	$5x10^{-4}$	$5x10^{-3}$
Steel bar	Elastic-perfect plasticity model	200	-420	-	420	-	-	-

* : measured value

In Table 1, E_0 is the elastic modulus of SFRS. Because it is generally difficult to estimate tensile material properties and ultimate deformation parameters of SFRS by load tests, the values indicated in Table 1 are determined by using back-calculation techiques.

The numerical analysis of the finite element models is performed by our developed program, based MATLAB code.

2.3 Strain softening behavior after post-peak load capacity

Spacone (1996)'s approach limit to predict behavior of SFRS after its post-peak load. In his approach, section equilibrium should be determined iteratively by structure state determination, not section equilibrium itself. This process enables the total structure state determination process to determine fast and efficiently. However it is difficult to satisfy equilibrium of finite element model, especially anisotropic material member after the peak load capacity under non-axial loading condition. Even if the analysis is switched to displacement control for effectiveness beyond peak load, section forces is not in equilibrium.

For predicting the softening behavior of SFRS and SFRS reinforced with steel bars after peak load capacity, a moment-curvature relationship of simply supported SFRS beam under the concentrated load is used. Moment distribution in longitudinal direction of simply supported beam is linear as shown in Fig. 3, regardless of material nonlinearity. As curvature at the center of beam increases beyond the peak moment point, equilibrium requires the moments in other parts of beam to reduce. If the material is assumed to unload elastically, using principle of virtual work, the displacement at the midpoint of beam is described as Eq. (1) or Eq. (2).

$$\delta = 2\int_0^{L/2} \left(x/2\right)\kappa(x)\,\mathrm{dx}, \tag{1}$$

$$\delta \approx \sum_{i=1}^{n_x} x_i \kappa_i \Delta l_i, \tag{2}$$

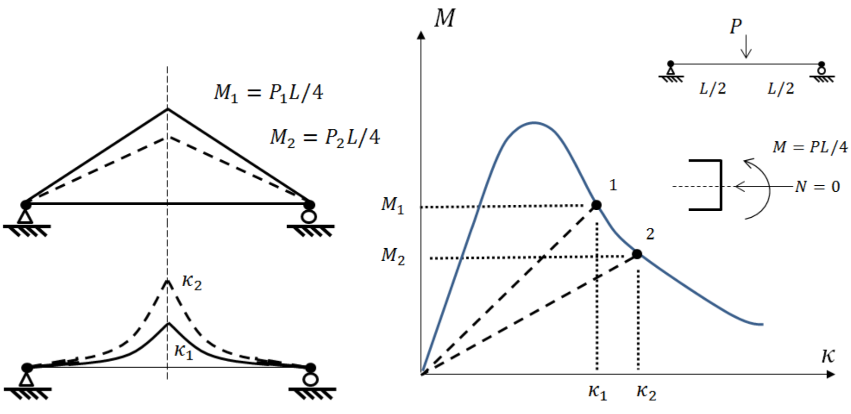

Fig. 3 Moment-curvature of 3 point flexural test

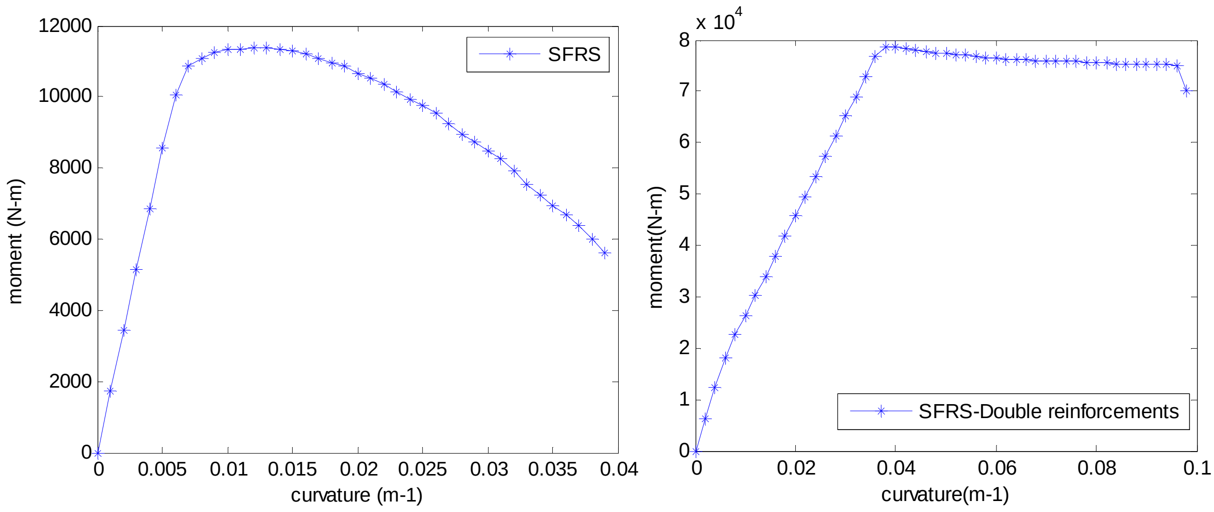

Fig. 4 Moment-curvature of 3 point flexural test

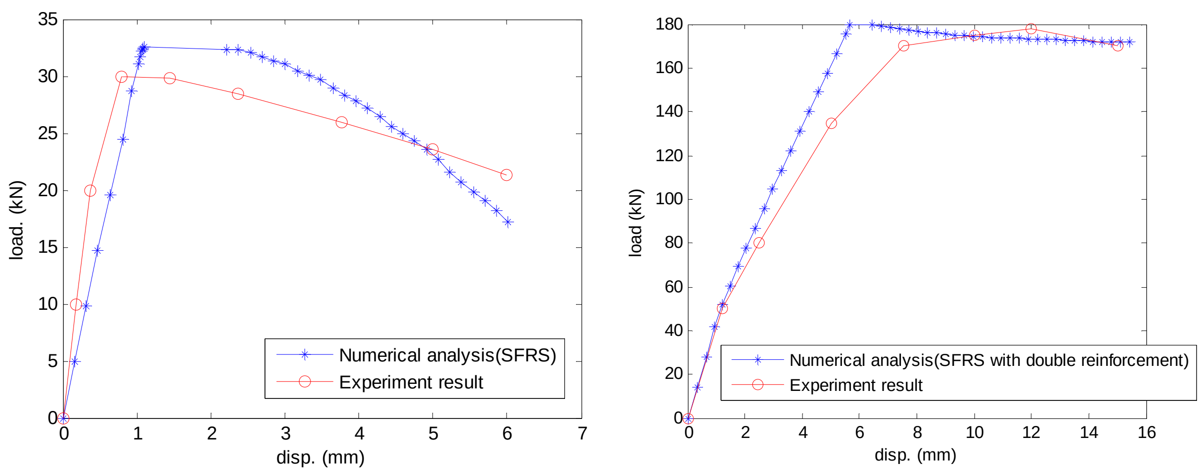

Fig. 5 Load-displacement at the midpoint of the specimens

where $x_i = (L/2) \times (M_i / M_0)$. M_0 and κ_0 represent the bending moment and the curvature at the mid-point of span, respectively. M_i and κ_i are given from a moment-curvature diagram. The moment-curvature diagrams for estimating behavior of SFRS and SFRS reinforced with steel bars are indicated in Fig. 4.

2.4 Results of numerical analysis

Load-displacement curves are indicated with 3 point flexural test by Park (2010) in Fig.5. It shows that the proposed approach can predict approximately the experiment results in pre-peak as well as post-peak response of SFRS and SFRS reinforced with steel bars. In the case of the SFRS member, the load capacities decrease dramatically after the applied point load reaches its peak value. The plat part of curve means that the steel fibers in tension region at the midpoint resist to the max and lose perfectly its tensile resistance. In the case of SFRS with double reinforcements, since the proposed SFRS constitutive relation is defined by using a set of lines, the slopes of numerical results in the initial part are stiffer than experiments' one. However, the numerical results approximately estimate the effects of reinforcements and the ultimate load capacity.

3. CONCLUSIONS

Simplified shotcrete with reinforced steel fibers constitutive model is proposed and demonstrated that it can be a good tool for estimating behavior of SFRS. This study shows that a simple SFRS structure is efficiently predicted its pre-response as well as post-response by using the fiber section model with moment-curvature analysis are used. The proposed approach can be useful for preliminary design of SFRS. It is also proved, by numerical study, that steel bars can be used as tunnel supports instead of H-section supports.

ACKNOWLEDGMENT

This study is supported financially by the Nation Research Foundation of Korea (No. 2010-0026196).

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