Numerical modelling of steel fiber reinforced tunnel segment subjected to flexure

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ABSTRACT

The use of steel fiber reinforced concrete (SFRC) in tunnel boring machine (TBM) based tunnel lining construction has gained popularity across the world for the past few decades due to its high toughness and improved durability performance compared to conventional reinforced cement concrete (RCC). In addition to the soil surcharge during the serviceable life, the precast tunnel segments experience bending stresses during the transient stage involving demoulding, stacking, and handling of the segments which could potentially lead to unforeseen critical cracks in the segment. The large-scale testing of precast segments is not always viable and can be very expensive. In this study, the SFRC tunnel segment is tested numerically under three-point bending using DiANA FEA software. The uniaxial stress-crack opening law in tension is obtained through inverse analysis which is performed by comparing experimental and predicted results from a global search optimization algorithm and further the results are compared with numerical result of the notched beam modelled using a discrete crack approach. To simulate the fracture behavior of SFRC tunnel segment under three-point bending, non-linear finite element analysis is performed using the smeared crack approach and the SFRC constitutive law obtained from the inverse analysis. Finally, the model is validated by comparing the results of numerical analysis with full-scale experiments performed on the tunnel segments.

KEYWORDS: *Steel fiber reinforced concrete, Inverse analysis, Smeared crack approach*

1. Introduction

Steel fiber reinforced concrete (SFRC) has gained popularity due to its good load bearing capacity and ductility. However, to use this material in tunnel segments, several levels of structural checks need to be executed. Based on different loading stages, the structural checks are divided into three categories such as transient, construction and service phase. Three loading stages during transient phase - demolding, stacking and handling cause bending stresses which could lead to cracking in the segment. Hence, it is imperative to assess the bending performance of the tunnel segment. The full scale structural testing on the tunnel segment is not always feasible due to time and economical constraints. In this context, finite element simulation is a good alternative technique to large scale experimental testing. By imposing appropriate loading and boundary conditions along with advanced material models, mechanical behavior of the tunnels can be simulated by non-linear finite element models. To accurately model SFRC tunnel segment, the material properties and the constitutive model has to be deduced experimentally. While the materials properties like elastic modulus and Poisson's ratio are easier to obtain experimentally, it is difficult to obtainuniaxial tensile constitutive relation of SFRC through direct tension test. The flexural tests under three- point bending configuration are initially performed on the notched SFRC beams and inverse analysis is performed through FEA modelling to determine the uniaxial constitutive law. Researchers have proposed several robust inverse analysis techniques including stepwise approach (Nanakorn and Horii(1996),

Kitsutaka (1997)), window-by-window strategy (Nour, Massicotte, de Montaignac and Charron (2015)), global fitting algorithm using different optimization algorithms (Sousa and Gettu (2006), Stephen et al. (2019)). In this study, inverse analysis based on Probabilistic Global Search Lausanne (PGSL) algorithm proposed by Stephen et al. (2019) is used to obtain constitutive law of SFRC.
The objective of this work is to numerically assess the mechanical behaviour of SFRC tunnel segment. This process involves determination of uniaxial constitutive law through inverse analysis, modelling and analysis of tunnel segment and to assess its performance through load-deformation curve, stress and strain plots and contours.

2. Inverse analysis

As it is difficult to obtain constitutive law of SFRC through direct tension tests, the constitutive law in the form of stress-crack opening ($\sigma - w$) relationship of SFRC under three-point bending tests is obtained by adopting inverse analysis approach. The inverse analysis procedure involves an iterative process that fits experimental data to determine the parameters defining the stress-crack opening curves. Load-crack mouth opening displacement (CMOD) curves from the three-point bend test of notched SFRC beams are used as input for the inverse analysis. Inverse analysis proposed by Stephen et al. (2019) based on Probabilistic Global Search Lausanne (PGSL) algorithm (Raphael et al. (2003) is performed by minimizing the sum of errors between the experimental and predicted loads. A tetra-linear tensile constitutive law is derived from inverse analysis, resulting in a good match between the experimental and predicted load-CMOD (Crack Mouth Opening Displacement) curve, as shown in Figure 1(a). The tetra-linear stress-crack opening law is shown in Figure 1(b), with the corresponding parameters summarized in Table 1.

a) b)

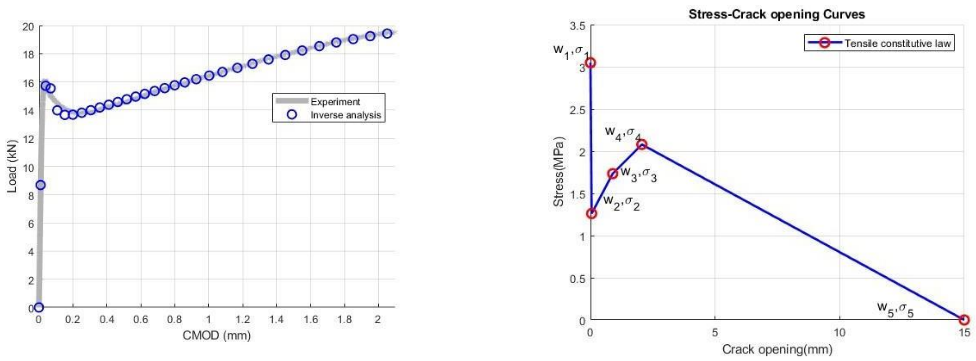


Figure 1: a) Load-CMOD curves: Experiment versus inverse analysis b) Tensile constitutive law of SFRC from inverse analysis

Table 1: Parameters of the tensile constitutive law obtained from inverse analysis

Parameters	Optimized values
$w1, \sigma1$	0, 3.048
$w2, \sigma2$	0.047, 1.260
$w3, \sigma3$	0.892, 1.733
$w4, \sigma4$	2.062, 2.079
$w5, \sigma5$	15, 0

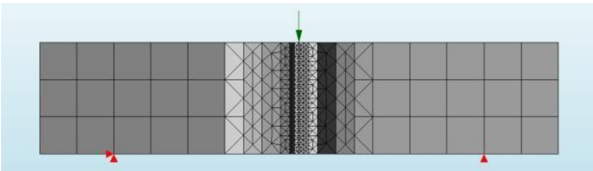
3. Non-linear finite element analysis

To simulate the behaviour of SFRC tunnel segment, the first step is to obtain the uniaxial stress-crack opening law through inverse analysis which involves modelling notched SFRC beam using discrete crack model. The deduced constitutive law obtained from inverse analysis is converted to stress-strain law using crack band-width parameter (Bazant and Oh (1983)). The resulting stress-crack opening law is used as input in the tunnel segment model which is based on smeared crack approach. Both the models are developed in a commercial finite element analysis software DiANA FEA 10.5.

3.1 Modelling of notched SFRC beams using discrete crack approach

Discrete crack approach (Originally proposed by Hillerborg et al.(1976)) is advantageous when the potential crack path is known apriori. The crack path is modelled using interface elements whereas the bulk is considered to be uncracked. For modelling the notched SFRC beams, discrete crack approach is suitable as it is known beforehand that the potential crack path will be along the notch. A simply supported beam with length (L) = 700 mm, width (b) = 150 mm, depth (d) = 150 mm, notch length (a_0) = 25 mm and span of the support (l) = 500 mm is subjected to centre-point loading according to the guidelines specified in EN 14651:2005. The parameters considered for the uncracked region are elastic modulus = 27 GPa (obtained from inverse analysis), and poisson's ratio = 0.2. The fracture is modelled using zero thickness interface elements and the tensile constitutive law obtained from inverse analysis is assigned to the interface elements. FE model of SFRC notched beam under three-point beding is shown in Figure 2(a). The interface elements follow three-point newton-cotes integration scheme. The dummy normal and shear stiffness for the interface elements are taken as 10^8 N/mm. The FE model shows good corelation with the experimental outcome as shown in Figure 2(b).

a)



b)

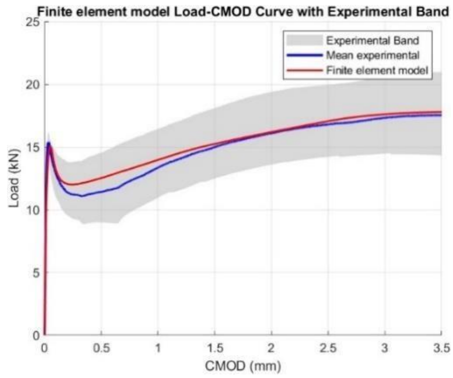
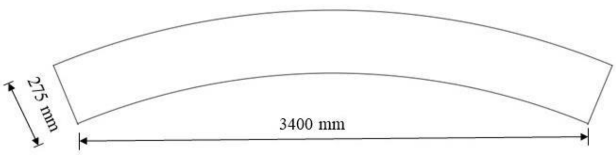


Figure 2: a) Finite element model for the notched SFRC beam b) Load-CMOD curves: Comparison between experimental and finite element model

3.2 Nonlinear finite element model of tunnel segment

The curved SFRC tunnel segment with outer radius of 3175 mm and inner radius of 2900 mm is modelled using smeared crack approach. The schematic and the finite element mesh of the tunnel segment model is shown in Figure 3. The stress-strain constitutive law is retrieved from stress-crack opening by using crack band width as equal to element size based on the assumption that one crack is smeared over a single element according to the Rots model available in DiANA FEA. The segment is discretized using regular eight noded quadrilateral elements of size 60 mm which is same as length of the steel fibre. The integration scheme of 2 × 2 gauss- legendre is used for all the elements of the mesh. One end of the curved segment is pinned and the other end has roller supports. The loading is imposed in the form of prescribed displacement over the three nodesof a element to simulate the loading correctly with the experiment. A non-linear analysis using newton- raphson algorithm is performed in 2000 load-steps to a

(a)



(b)

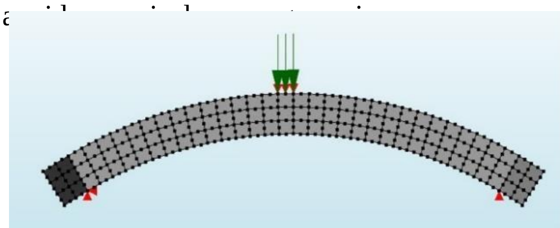


Figure 3: a) Schematic of the tunnel segment b) 2D finite element model for the tunnel segment

4. Results

The results of FE model of tunnel segment are compared with the experimental results of large-scale tunnel segment testing. The load-mid-span deflection curve shows a good match with the mid-span linear variable displacement transducer (LVDT) data. The stiffness and first crack load values match exactly as depicted in figure 4. The finite element results are found to be sensitive to mesh size, crack band-width parameter. A very fine mesh overpredicts the load and a very coarse mesh brings numerical instability in the model. Hence, a mesh size of 60 mm is chosen to balance numerical stability and computational efficiency.

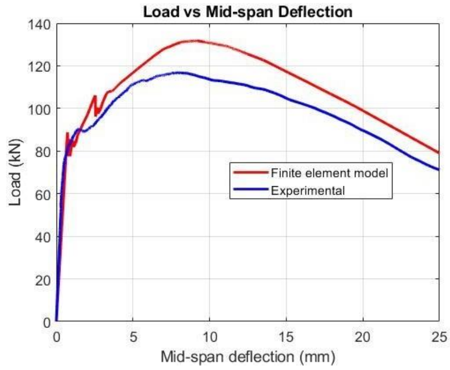


Figure 4: Comparsion between experimental and model predicted load versus mid span deflection curves

5. Conclusions

This study successfully employed a non-linear finite element model to predict the flexural response of a curved tunnel segment, accurately capturing elastic behavior and the first cracking load in agreement with experimental results. The predicted load-deflection curve closely matched the experimental response in the post-cracking zone, demonstrating the model's capability to replicate complex mechanical behavior under flexural loads. These findings underscore the effectiveness of finite element simulations in analyzing tunnel segment behavior under flexure.

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