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Research Paper

Simultaneous pattern and size optimisation of rock bolts for underground excavations

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ABSTRACT

Designing a rock bolt reinforcement system for underground excavation involves determining bolt pattern, spacing, and size. In this paper, a topology optimisation technique is presented and employed to simultaneously optimise these design variables. To improve rock bolt design, the proposed technique minimises a displacement based function around the opening after bolt installation. This optimisation technique is independent of the material model and can be easily applied to any material model for rock and bolts. It is also extremely flexible in that it can be applied to any mechanical analysis method. To illustrate the capabilities of this method, numerical examples with non-linear material models and discontinuities in the host rock are presented. It is shown that the complexity of systems optimised using this approach is only restricted by limitations of the method used to analyse mechanical system responses.

1. Introduction

To maintain underground excavation stability and prevent failures, it is typically necessary to increase the integrity and stiffness of rock mass by means of additional reinforcement or support. Determining the best reinforcement distribution is a vital and challenging step in excavation design which can be classified as an optimisation problem. Complex optimisation problems such as this one must generally be solved iteratively. With each iteration, the system must be analysed and then updated based on its responses. Due to the complex behaviours of ground materials and complications such as rock discontinuities, a powerful analysis method is required to address this problem.

Over the last few decades, numerical analysis methods have been advanced and widely adopted in tunnelling design. The reader can refer to the following review papers on numerical methods used in tunnelling and rock mechanics: Gioda and Swoboda [13], Jing and Hudson [15], and Bobet et al. [7]. These methods enable one to develop acceptable approximations for numerous practical cases. A prominent advantage of numerical analysis methods over analytical and empirical methods lies in their flexibility and ability to consider important factors such as excavation process and construction sequence effects on behaviours of surrounding geomaterials and support systems [9]. Furthermore, sophisticated material models and various geological conditions and tunnel features can be conveniently simulated using numerical methods.

On the other hand, topology optimisation methods have consistently been improved over the last two decades. For more information on various topology optimisation methods and recent developments in this area, the reader can refer to review works of Bendsøe and Sigmund [4], Rozvany [26], and Deaton and Grandhi [10]. Topology optimisation methods can be used to identify the optimal material distribution for a design domain. This paper presents an extended topology optimisation technique that employs a numerical analysis engine to optimise rock bolt design for underground excavations. The finite element method is used as the numerical analysis method given its widespread availability and capacity to address complex geomechanical problems. It should be noted, however, that any other suitable numerical analysis method can be used as an alternative to the finite element method in conjunction with the proposed optimisation method.

In a seminal work, Bendsøe and Kikuchi [3] presented the first practical general-purpose structural topology optimisation method. Commonly referred to as the "homogenisation method", the methods introduction spurred numerous subsequent studies in the field. Other notable topology optimisation methods include the Solid Isotropic Material with Penalisation (SIMP) method and the Bi-directional Evolutionary Structural Optimisation (BESO) method [11]. The SIMP method was first presented by Bendsøe [2]. In this method, a power-law relationship between the

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elasticity tensor and material density is assumed. Then based on a sensitivity analysis of a chosen objective function the material density of each element is updated iteratively. The BESO method was initially presented by Querin [24], Querin et al. [25], and Yang et al. [29]. Using this method, one can optimise material distributions by iteratively removing inefficient elements and by adding more elements around the most efficient areas of the design domain.

In the realm of underground excavations, topology optimisation applications were first studied by Yin et al. [32] and Yin and Yang [30,31]. In these early works, an artificial homogenised isotropic material with a larger elastic modulus was used to model reinforced areas around the tunnel. Linear elastic material models have been used for both host and reinforced rock. Homogenisation and SIMP methods have been employed in these works to determine the optimal distribution of homogenised reinforced material around underground openings. Using the same modelling technique, Liu et al. [19] employed a fixed-grid BESO technique to optimise reinforcement distributions around tunnels. Employing the same modelling assumptions and using the BESO method, Ghabraie et al. [12] examined simultaneous shape and reinforcement optimisation techniques for underground excavations. Modelling assumptions in this area were improved by Nguyen et al. [21] where non-linear elasto-plastic material models were considered in both original and reinforced rock, and the BESO method was used to optimise reinforced material distributions.

Limitations common to all of these aforementioned studies include the usage of homogenised reinforced materials and the simplification of assumptions involved. Given the unidimensional geometry of rock bolts, an equivalent homogenised reinforced rock material will not be isotropic [5,6]. However, in all of these works, isotropy is assumed for reinforced rock material. Moreover, final optimised solutions obtained using such a modelling technique only reflect areas to be reinforced and do not generate a clear rock bolt pattern. The user must therefore post-process or intuitively interpret results before applying them.[1]

To overcome these shortcomings and obtain representative results, rock bolts must be explicitly modelled using linear inclusions embedded in rock mass. A suitable topology optimisation technique may then be employed to optimise rock bolt patterns around the opening. The authors recently submitted a paper in which this explicit modelling technique was used in conjunction with the SIMP method to optimise the cross-sectional area of individual rock bolts in a given pattern [22]. In this paper, we extend this approach further by simultaneously optimising the pattern, length and cross-sectional area of rock bolts.

The remainder of this paper is organised as follows. First, tunnel excavation and reinforcement system modelling approaches are presented. Design variables are then introduced in Section 3. The objective function and optimisation problem statement are presented in Section 4. This is followed by a sensitivity analysis presented in Section 5. Procedures for updating design variables are described in Section 6. A simple example is then presented to illustrate the application of the proposed method. Impacts of tunnel shape and geological conditions on rock bolt design are then examined through several examples to further demonstrate the capabilities of this method.

2. Modelling of reinforcement systems and excavation sequences

The finite element method is employed for numerical modelling and analysis. It is assumed that the tunnel is long and straight enough to satisfy the plane strain condition. Rock bolts and shotcrete linings are used for reinforcement. The thickness of the shotcrete lining is assumed to be fixed at 100 mm. One element is used to model the thickness of the shotcrete lining around the opening.

Rock bolts can be classified into end-anchored and continuously anchored bolts. In this paper, only end-anchored bolts are considered, mainly due to simpler modelling techniques involved relative to continuously anchored and fully grouted bolts. However, the same optimisation approach can also be extended to continuously anchored bolts. In this case, rather than considering one truss element per bolt, each bolt must be divided into several truss elements, and all these elements must be modified together. The authors plan to address problems associated with continuously anchored bolts in a separate work.

In simulating thin inclusions such as rock bolts, bending stiffness can be neglected [8,18]. Hence, for purposes of simplicity, truss elements are used here to model bolts. The Abaqus/Standard finite element package is used to perform finite element analyses given its flexibility and capabilities.

As a two-dimensional model is considered, the three-dimensional squeezing effect prior to bolt installation cannot be modelled directly. Instead, the convergence-confinement method [23] is employed.

The entire excavation and reinforcement installation process is modelled in three steps as depicted in Fig. 1. The first step involves simulating pre-excavation conditions. In this step, *in situ* stress ($\boldsymbol{\sigma}_0$) is applied while opening surface nodes are restrained, and surface traction $\boldsymbol{\tau} = \mathbf{n} \cdot \boldsymbol{\sigma}_0$ is then calculated (Fig. 1a). Here, $\mathbf{n}$ denotes the inward unit vector relative to the surface opening. By multiplying surface traction by 1 m run of the tunnel and then lumping values at nodes, nodal values of reaction forces, hereafter denoted as $\mathbf{t}$, can be determined.

The second step involves simulating opening convergence prior to reinforcement system installation. At this stage, opening surface node restraints are removed while a surface traction level equal to a ratio of reactions occurring in the previous step ($\mathbf{f} = \beta\mathbf{t}$) is applied (Fig. 1b). The value of β can be assumed based on longitudinal displacement profiles. For the cases solved in this paper, based on improved longitudinal displacement profiles provided by Vlachopoulos and Diederichs [28], a maximum of 70% of radial displacement will manifest prior to bolt installation, and a conservative value of $\beta = 0.3$ is adopted accordingly.

In the third and final step, the shotcrete lining and rock bolts are added to the model, and surface traction is removed (Fig. 1c). Here, we assumed that bolts experience the entire excavation load of the tunnel and deemed them a permanent support system. This can be easily adjusted if bolts are only used to withstand a share of the excavation load prior to main support system installation. In such a case, the traction force $\beta\mathbf{t}$ employed in step 2 should not be removed in step 3, but only reduced to $\beta'\mathbf{t}$, where $\beta' < \beta$ and β' should be found based on the distance from the face at which the permanent support system is to be installed.

3. Design variables

The locations of bolt endpoints and cross-sectional areas are considered as design variables. We denote the location of the endpoint of bolt b by the coordinates (x_b, y_b) and its cross-sectional area by a_b. The number of bolts is denoted with m. It should be noted that by allowing a_b to take a value of zero, it is possible to remove bolt b from the design and hence change the spacing between adjacent bolts. Additionally, controlling (x_b, y_b) controls both bolt b length and orientation. Hence, using these three variables for each bolt, we can identify the rock bolt design around the opening.

[1] See Section 7.4 in Nguyen et al. [21] or Fig. 10d in Liu et al. [19].