THERMAL COUPLING EFFECT ANALYSIS OF GEOTECHNICAL ENGINEERING REINFORCEMENT MATERIALS BASED ON FINITE ELEMENT ANALYSIS

by

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In the analysis of material thermal coupling effect, the stress-strain relationship of material is seldom considered, which leads to the greater influence of material grid strain effect, which leads to the poor accuracy of material thermal coupling effect analysis. Based on this, this paper puts forward the thermal coupling effect analysis of geotechnical engineering reinforcement materials based on the finite element analysis. According to the concept of cooling zone, the thermal resistance value of the material is calculated. Combined with the stress relationship and thermal resistance value, the thermal coupling effect of the material is analyzed by finite element discretization. In the experiment, the geotechnical engineering reinforcement material is used as the analysis object to analyze the material thermal coupling effect. The result of the proposed method is closer to the actual situation than that of the traditional method. The accuracy rate of the material thermal coupling effect analysis is up to 98%, which proves that the proposed method is feasible.

Key words*: thermal coupling, finite element analysis, strain effect, reinforcement material, thermal resistance value*

Introduction

At present, the main analysis methods of thermal coupling problem at home and abroad mostly use sequential coupling method. The development of multi field coupled dynamic analysis in domestic literature research includes aerodynamic heating, transient temperature field analysis, thermos elastic coupling and thermal mode analysis, mathematical model and solution method of coupled dynamic analysis, *etc*. [1]. There are many researches on multi field coupling in foreign countries, but the research on thermal coupling is similar to that in China, and the analysis method is mainly sequence coupling method. Some other methods use sequential coupling model to simulate the residual stress of surface grinding by finite element method, or analyze the thermal induced vibration of thin cantilever beam sub-

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jected to sudden uniform heat flow [2, 3]. However, there are some problems in these methods, such as the inaccuracy and time-consuming, which are not conducive to the analysis of the thermal coupling effect of geotechnical engineering reinforcement materials.

Based on the aforementioned problems, the thermal coupling effect analysis method of geotechnical engineering reinforcement materials based on finite element analysis is proposed in this paper. The finite element analysis method is introduced. Finite element method is a kind of numerical approximate calculation and analysis method by computer.

Finite element analysis model and confirmation of stress relationship

Establishment of finite element analysis model

In order to complete the thermal coupling effect analysis of geotechnical engineering reinforcement materials, the finite element analysis model needs to be built with the help of finite element method. The basic stress situation of engineering reinforcement materials is determined by establishing the finite element analysis model to ensure more accurate thermal coupling analysis in the future [4, 5].

Considering the stress-strain relationship of engineering reinforcement materials in use, it is expressed as three strain stages, namely:

$$ {}^{t}\tilde{e} \geq 0 \text{ , } 0\rangle {}^{t}\tilde{e} \geq \tilde{e}_c \text{ , } \tilde{e}_c\rangle {}^{t}\tilde{e} \geq \tilde{e}_u $$

where $\tilde{e}_c$ is the uniaxial strain force corresponding to $\tilde{\sigma}_c$, $\tilde{\sigma}_c$ – the maximum uniaxial compressive stress of the material, $\tilde{e}_u$ – the uniaxial ultimate compressive strain of the material, ${}^{t}\tilde{e}$ – the initial stress of the material. If the material is in use and is under pressure, before the failure stress $\tilde{\sigma}_t$ of the material is reached, the strain relation is linear, but when ${}^{t}\tilde{e} \leq 0$, the finite element analysis model is:

$$ \frac{{}^{t}\tilde{\sigma}}{\tilde{\sigma}_c} = \frac{\left(\dfrac{\tilde{E}_0}{\tilde{E}_s}\right)\left(\dfrac{{}^{t}\tilde{e}}{\tilde{e}_c}\right)}{1 + A\left(\dfrac{{}^{t}\tilde{e}}{\tilde{e}_c}\right) + B\left(\dfrac{{}^{t}\tilde{e}}{\tilde{e}_c}\right)^2 + C\left(\dfrac{{}^{t}\tilde{e}}{\tilde{e}_c}\right)^3} \tag{1} $$

where ${}^{t}\tilde{\sigma}$ is the initial natural stress of the material, $\tilde{E}_0$ – the uniaxial initial modulus of elasticity, $\tilde{E}_s$ – the Secant modulus representing uniaxial maximum stress $\tilde{E}_s = \tilde{\sigma}_c / \tilde{e}_c$, *A*, *B*, *C* represents the material stress values under three strain stage relationships.

Determination of material stress relationship

On the basis of the aforementioned finite element analysis model, the stress relationship among the three stages is determined:

$$ A = \frac{\left[\dfrac{\tilde{E}_0}{\tilde{E}_u} + \left(P^3 - 2P^2\right)\dfrac{\tilde{E}_0}{\tilde{E}_s} - \left(2P^3 - 3P^2 + 1\right)\right]}{\left[\left(P^2 - 2P + 1\right)p\right]} \tag{2} $$

$$ B = \left[\left(2\frac{\tilde{E}_0}{\tilde{E}_s} - 3\right) - 2A\right] \tag{3} $$

$$C=\left[\left(2-\frac{\tilde{E}_0}{\tilde{E}_s}\right)+A\right] \tag{4}$$

where P is the tensile degree of the material.

When materials are in uniaxial stress state in different structures, the stress-strain relationship is relatively simple. At present, the load material used in geotechnical engineering reinforcement is often a brittle elastic material, with no yield strength and only ultimate strength. When the stress of a layer of composite reaches the ultimate tensile strength, it loses any stiffness and strength. The stress-strain relationship of orthotropic materials is:

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0\\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{bmatrix} \tag{5}$$

where σ is the stress values applied to the composite and ε – the strain force applied on the composite.

Material thermal resistance and temperature field correction

Material thermal resistance value acquisition

In order to improve the accuracy of the analysis of thermal coupling effect of materials, it is necessary to calculate the thermal resistance of materials. In this paper, the concept of cooling region is introduced and applied to the problem of radial thermal expansion of thin plate geometry model [6]. This method assumes that a uniform isothermal heat source is applied at the center of the upper surface of the substrate. In the numerical simulation, the heat source can be set as a material with infinite thermal conductivity (k = 10000 W/mK). The calculation of thermal resistance is shown in fig. 1.

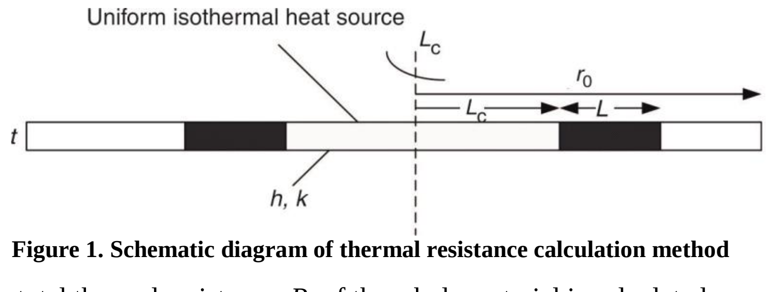

Figure 1. Schematic diagram of thermal resistance calculation method

The total thermal resistance, R, of the whole material is calculated:

$$R=\frac{1}{\varphi h L_c^{\,2}} \tag{6}$$

where h is the thermal expansion of the material after the heat source and L_c – the characteristic length of the cooling zone of the material, the characteristic length of cooling zone is defined:

$$L_c = \sqrt{kt / h} \tag{7}$$

where k is the heat source area of the material affected by the heat source and t – the substrate thickness of the material. To determine the convective thermal resistance value in 1-D thermal resistance of the material, the calculation method is:

$$R_0 = \frac{1}{A_p h} \tag{8}$$

After confirming the value of convective thermal resistance in the material, the thermal coupling of the material is analyzed.

Correction of material temperature field

Suppose that on a certain element of the model material, the temperature at time, t, is T, the external force of the joint is $\{F\}^e$, the node displacement is $\{\delta\}$, it should be $\{\varepsilon\}$, the stress is $\{\sigma\}$, and d – the elastic region. In the moment of $t + dt$ the principle of virtual displacement can be used to get:

$$\{d\delta\}^T \{F + dF\}^e = \int\int_v \{d\sigma\}^T [B]^T (\{\sigma\} + \{d\sigma\}) \mathrm{d}V \tag{9}$$

where [B] is the unit strain matrix, since the material object is in equilibrium at t time, it is concluded that:

$$\{F\}^e = \int\int_{\triangle v} [B]^T \{\sigma\} \mathrm{d}V \tag{10}$$

According to eqs. (9) and (10), it can be concluded that:

$$\{dF\}^e = \int\int_{\triangle v} [B]^T \{d\sigma\} \mathrm{d}V \tag{11}$$

In the analysis, the thermal coupling effect of materials is easily affected by friction. In order to improve the analysis accuracy of the proposed method, it is necessary to modify the temperature field of the material. The thermal interaction process of inertia friction welding is complex, and the friction directly determines the heat generated by the friction surface. Through the influence of temperature change on physical parameters and the thermal stress generated by temperature change, the temperature change affects the deformation of the material; The heat generated by plastic deformation affects the temperature of the work piece joint during the welding process [7]. The temperature field depends on the heat generated by the mutual friction and plastic deformation (stress-strain field) of the welding work piece. The temperature field and stress-strain field influence each other [8-11]. The interaction of temperature, material properties, friction and upset pressure makes the inertia friction welding process highly nonlinear. In this paper, the calculation of the temperature field is obtained by the two-dimensional axisymmetric nonlinear heat conduction equation, namely:

$$\rho C_p(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left[k(T)\frac{\partial T}{\partial r}\right] + \frac{k(T)}{r}\frac{\partial T}{\partial r} + \frac{\partial}{\partial z}\left[k(T)\frac{\partial T}{\partial z}\right] + q, (r, z) \in \Omega \tag{12}$$

where $k(T)$ is the thermal conductivity associated with temperature, $C_p(T)$ – the temperature dependent heat capacity, ∂ – the temperature gradient of the material in the direction outside the boundary, and ρ – the density. Where q is calculated:

$$q = a\overline{\sigma}\overline{\varepsilon} + q_i \tag{13}$$

where $\bar{\sigma}$ is the equal effects, $\bar{\varepsilon}$ – the equivalent rate of change, a – the thermal efficiency of plastic deformation, and q_i – the internal latent heat of the material. The 2-D axisymmetric large deformation elastoplastic model is used to calculate the stress-strain field:

$$\int_{\nabla 0} S_{ij}\delta E_{ij}\mathrm{d}V = \int_{\nabla 0} P_{oi}\delta u_j \mathrm{d}V + \int_{S_0 T} T_{oi}\delta_j \mathrm{d}s \tag{14}$$

where S_{ij} is the Kichhoff stress tensor, δE_{ij} – the Green strain tensor, δu_j – the virtual displacement vector, and P_{oi} and T_{oi} – the unit volume force component and the unit area force component acting on the deformable body, respectively, [12-14]. After the finite element discretization, the governing equations of thermal mechanical coupling model of inertia friction welding process are:

$$\begin{gathered} K(T)u = f \\ C(T)\dot{T} + K_1(T)T = Q \end{gathered} \tag{15}$$

Experimental analysis

Experimental environment

In order to verify the effectiveness of the proposed method, simulation experiments are carried out. The experiment is operated on Windows 10 system, and its running memory is 8 GB. In the experiment, a geotechnical engineering reinforcement material is taken as the analysis object, in which the number of specimens is six and the size is 2.4 m × 0.4 m × 0.4 m, after heat source treatment, the left end of the material is placed in a constant temperature environment of 80 °C. The right end of the specimen is placed in the external environment without any measures.

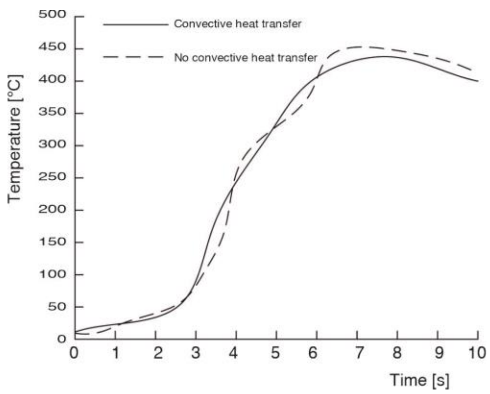

Figure 2. Effect of convective heat transfer coefficient on temperature calculation

Analysis of experimental results

In order to verify the scientific effectiveness of the proposed method, the experiment analyzes the influence degree of the convective heat transfer coefficient on the temperature calculation results, and analyzes the influence changes under the conditions of using convective heat transfer and no convective heat transfer. The experimental results are shown in fig. 2.

In order to further verify the feasibility of the proposed method, the welding process of reinforcement materials in geotechnical engineering is simulated, and the distribution of radial stress along the axial direction in different welding time is analyzed. The experimental results are shown in fig. 3.

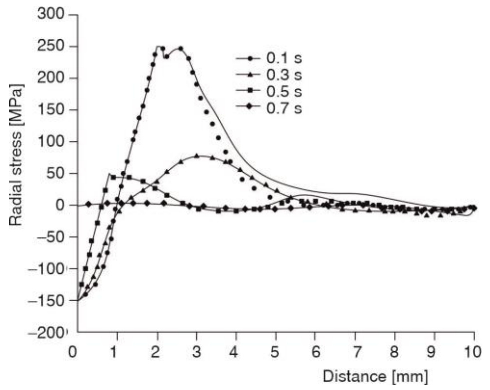

Figure 3. Analysis of radial stress distribution along the axial direction

As shown in fig. 3, during the initial welding stage (0.1 seconds ago), the welding joint temperature is low, no plastic deformation

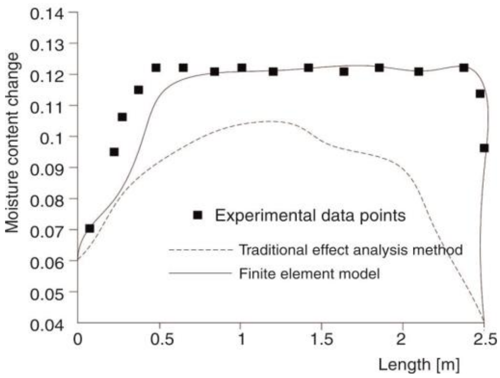

Figure 4. Moisture content distribution inside the material

occurs, and the radial stress is almost zero. With the increase of welding time, obvious plastic deformation occurs in the welded joint, the compressive stress is near the friction surface, and the tensile stress appears in the area far away from the friction surface. When the welding heating is completed, the compressive stress and tensile stress reach the maximum value, and these stress values meet the operation standard, which verifies the feasibility of the proposed method.

The simulation results of the finite element analysis model and the simulation results of the traditional thermal coupling effect analysis method are compared with the experimental data. The experimental results are shown in fig. 4.

It can be seen from fig. 4 that the results of temperature and humidity calculated by the linear coupling theory of moisture and heat are consistent with the experimental data. However, there are also shortcomings: the linear coupled humidity diffusion theory keeps the analysis materials on the initial drying surface before drying, which leads to the drying speed of reinforcement materials relatively slow compared with the actual situation, so as to keep balance with the external environment humidity this state takes a long time.

Conclusion

In this paper, based on the finite element analysis of geotechnical engineering reinforcement material thermal coupling effect analysis, through the finite element analysis of the material, confirm the material stress, after the thermal coupling effect analysis, to ensure the accuracy of the effect analysis results. Compared with traditional methods, it has the following advantages:

- The influence of the convective heat transfer coefficient on the temperature calculation results is consistent with the theoretical results.
- The proposed method is used to analyze the distribution of moisture content in the interior, and the analysis effect is good.
- The accuracy of the method is up to 98% and it has certain reliability.

However, this paper found that when the materials are connected by welding method, it is easy to have special cases. At present, the finite element algorithm or finite element software are difficult to ensure accurate modeling, so further research is needed.

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