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Automatic thermal analysis of gravity dams with fast boundary face method

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ABSTRACT

It is well recognized that the dam's construction schedule has significant influences in long-term concrete temperature, whose variations may produce local thermal stress and thus result in damage and cracking. This paper describes a methodology for predicting the thermal evolution of dams during their construction by the boundary face method (BFM). This work involves the following aspects: (1) the BFM is integrated into the UG-NX, making the analysis performed entirely within the CAD environment; (2) two kinds of new elements, i.e. tube element and element with negative parts are proposed to deal with cooling water pipes embedded in dams; (3) a domain number sequence optimization method is proposed for multi-domain problems for the best band of the assembling system matrix; (4) a geometric mapping cross approximation (GMCA) method is proposed to make the low-rank representation of the BIE more convenient and efficient; (5) the quasi-initial condition method for transient thermal problems is implemented and a time step scaling method is proposed to solve the instability problem in case of short time steps. Benchmark examples are presented and compared with other solutions by the FEM.

1. Introduction

It is widely recognized by engineers that the high temperature generated in the concrete due to the hydration heat of the cement paste is one of the main factors that result in fractures and damage for concrete hydraulic structures during their construction. Various aspects of thermal stresses in concrete dams have been investigated and reported using finite element method (FEM), but many problems of calculating thermal stresses in concrete masses still do not have a satisfactory solution. Moreover, the results reported by different researchers are different or even contradict to each other. The reason for this may owe to that the FEM has the following intrinsic drawbacks:

(1) Many kinds of abstract element, e.g. beam element, shell element, bar element, spring element, etc., are used in the FEM. These elements are all based on some mathematic assumptions. Selection of proper element type and reasonable explanation to the computational results require sound theoretical background, good knowledge of all elements performance and rich experience in numerical analysis.
(2) The analysis automation of the FEM is presently at very low level. As the FEM model (approximate grid model) is completely different from the CAD model (continuous parametric model), not only in geometry and topology, but also in representation data structure. This makes the interaction between CAE and CAD extremely difficult.
(3) The task of proper meshing for the FEM analysis is challenging and keeps the most critical part of the analysis. To make a dam meshable, the geometry of the dam structure is often modified and simplified. In the modification, small sized features at the connecting area between different parts of the structure are simply omitted. These features, however, are most possibly the places where local stress concentrations take place and cracks originate from. Moreover, further assumptions are required to connect different kinds of elements in the assembled matrix, e.g. connection between solid and shell elements. This leads to much worse accuracy for the stresses.
(4) The FEM is based on the equivalent weak form of the governing equation and the boundary conditions of the BVP. The trial functions in the FEM formulation must be at least C1 continuous. The C1 continuity requirement for the trial function increases the difficulty of constructing the elements, especially shell and beam elements, and leads to a number of contradictions, e.g. the contradiction between conforming and non-conforming elements, accurate integration and locking problems, reduced integration and hourglass modes, accuracy and stability in penal function method, etc. It is just guaranteed that an FEM solution converges when the element size approaching zero. Therefore, errors of the FEM come from

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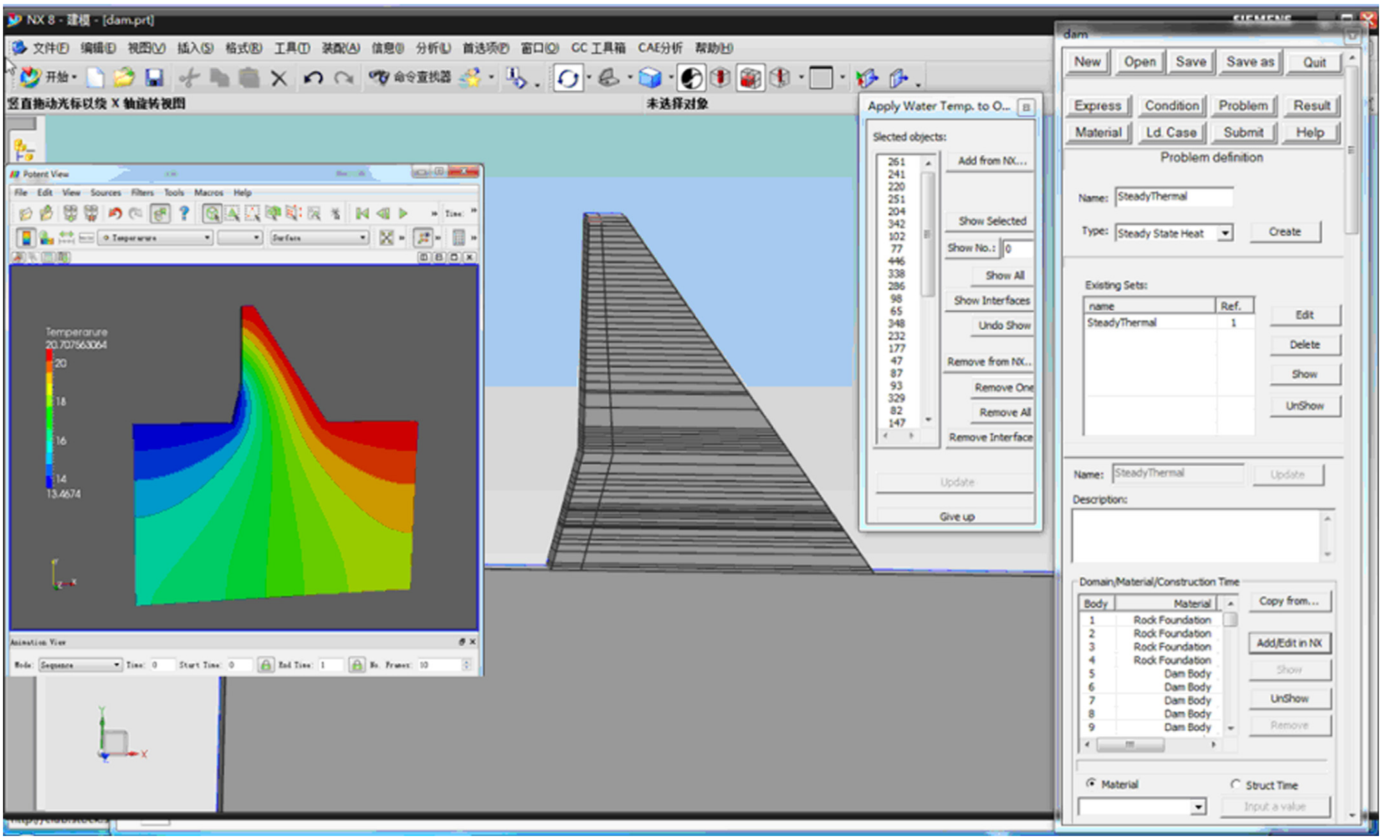

Fig. 1. UI of the Potent 1.0.

not only the approximation of the trial function but also from the "weak form" theory. Meanwhile, for a stress analysis by FEM, as stresses are calculated from the derivatives of displacements, the accuracy for stresses is lower by one order than displacements. In many cases, however, engineers are more concerned by the stress values.

To overcome the above problems, we have put forward the concept of complete solid stress analysis (CSSA) [1] and proposed the boundary face method (BFM) [2,3] based on the boundary integral equation (BIE) [4–8] to carry out the CSSA. In most cases, the BFM requires only boundary mesh, which can be obtained by discretizing each piecewise continuous panel of the body's surface without restriction of element connectivity, hence, considerably simplifies the discretization task. Moreover, it uses the parametric representation of domain surfaces, only. Such representation is used in any CAD software and can be accessed in commercial packages via Open Architecture features (usually the in-process COM servers/objects can be exploited). This may considerably simplify the data pre-processing and lead to substantial resources savings.

Our contributions are as follows:

1) Integrating the BFM into UG-NX, making the conductions of the analyses entirely within the CAD environment.
2) Proposing two kinds of new elements, i.e. tube element and element with negative parts. These elements have been successfully used to deal with cooling water pipes in dam.
3) Proposing a domain number sequence optimization method for solving multi-domain problems, which can deal with arbitrary inter-domain connections and get best efficiency by optimizing the band of the assembling system matrix.
4) Proposing a geometric mapping cross approximation (GMCA) method [9], which is equivalent to ACA but without iteration. The GMCA makes the low-rank representation of the BIE more convenient and efficient.
5) Implementing a quasi-initial condition method for transient thermal problems, and proposing a time step scaling method to solve the instability problem occurs in case of short time steps. (This is the case for dam simulation, as the heat conductivity of concrete is small but its hydration speed is relatively high).

2. Implementation of the BFM for dam simulation

2.1. Integration of the BFM into UG-NX

A primary version of CSSA software (Potent 1.0) has been developed. This software is completely integrated into the environment of the well known CAD package UG-NX (see Fig. 1). So far, the Potent 1.0 is able to solve problems in theories of static elasticity [10], steady state [11] and transient heat transfer [12] and acoustics [13]. Details can be found at the web site: http://www.5aCAE.com.

The Potent 1.0 is not only more accurate and efficient than most well known commercial CAE packages (e.g. NASTRAN, ANSYS, etc.), but also exhibits the following extraordinary merits:

1) Analysis can be easily performed by clicking some buttons in the UI of the NX-UG. It is not necessary for the users to master the knowledge about computational mechanics but just knowledge about material mechanics. With correctly imposed boundary conditions, accurate results can be obtained.