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An efficient on-line algorithm for the optimal design of multi-material structures under thermal loads

S.Z. Feng, X. Han*, G. Wang

School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, PR China

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ABSTRACT

In this study, the edge-based smoothed finite element method (ES-FEM) and reduced-basis method are combined to form an efficient on-line algorithm for the optimal design of multi-material structures under thermal loads. The ES-FEM is utilized to construct the heat transfer stiffness matrix, which is much more accurate than traditional FEM. Then, the reduced-basis method is developed as a forward solver to obtain thermal responses of multi-material structures, which can significantly reduce the computational effort of each forward analysis. Finally, the genetic algorithm is employed as the inverse solver to determine appropriate value of each design variable. Several numerical examples are fully investigated and it is shown that the presented algorithm is accurate and efficient enough for the optimal design of multi-material structures.

1. Introduction

In the past several years, the development of emerging manufacturing technologies such as solid free-form fabrication or rapid prototyping offers the possibility to make multi-material structures, which is usually made by two or more kinds of materials [1]. The properties of such structures can be adjusted with great flexibility through controlling the material composition and the desired performances can be easily obtained. Multi-material structures often work under high temperature environments and the related optimal design of structures has become an important issue in practical engineering. In general, it is very difficult to design just by intuition or experience and hence, effective optimization algorithms are needed for engineers. In order to guarantee the practicability of these algorithms, the most crucial part is to obtain the accurate thermal responses of multi-material structures with high efficiency. It means that accurate forward analysis and efficient inverse analysis are both needed to construct such an algorithm [2].

So much research works have been done focusing on dealing with heat transfer analysis [3–5]. For problem that is hard to obtain analytical solutions, numerical methods are widely utilized to calculate the thermal responses of engineering structures, such as finite element method (FEM) [6], finite volume method (FVM) [7], meshless method [8], point interpolation method (PIM) [9,10], etc. Among all these methods, the FEM has been proved to the most powerful tool for such analysis. However, the FEM has an inherent shortcoming known as overly-stiff phenomenon, especially when linear triangular or tetrahedron meshes are used [11,12], which can be easily generated especially for structures with complex geometries. In order to overcome this shortcoming, Liu proposed a generalized gradient smoothing technique and applied it to standard FEM [13–17]. Inspired by Liu's work, a series of smoothed finite element methods have been developed and widely used for various engineering problems, such as the node-based smoothed finite element method (NS-FEM) [18,19], the edge-based smoothed finite element method (ES-FEM) [20–24], the cell-based smoothed finite element method (CS-FEM) [25], etc. Among these smoothed finite element method, the ES-FEM has been proved to posses many excellent features, which can be easily formulated based on existing FEM codes. The ES-FEM works well with triangular meshes and can provide much more accurate solutions than traditional FEM [26]. In addition, the ES-FEM can be conveniently extended to solve three dimensional problems, which is called face-based smoothed finite element method (FS-FEM) [27–29]. So far the ES-FEM has been successfully extended to deal with 2D and 3D heat transfer problems and accurate thermal responses of structures can be obtained based on triangular or tetrahedron elements [30–33].

With regard to improving the efficiency of optimization, the key step is to evaluate thermal responses of structures rapidly [34–38]. It is quite obvious that the total computational effort will be extensive if the computational time for one forward analysis is too long. This is due to the fact that a large number of forward analyses will be needed especially for multi-variable or multi-objective optimization cases. Some fast computation technologies have been proposed and developed for engineering analysis, such as reduced-basis method [39], multi-grid

* Corresponding author.
E-mail address: hanxu@hnu.edu.cn (X. Han).

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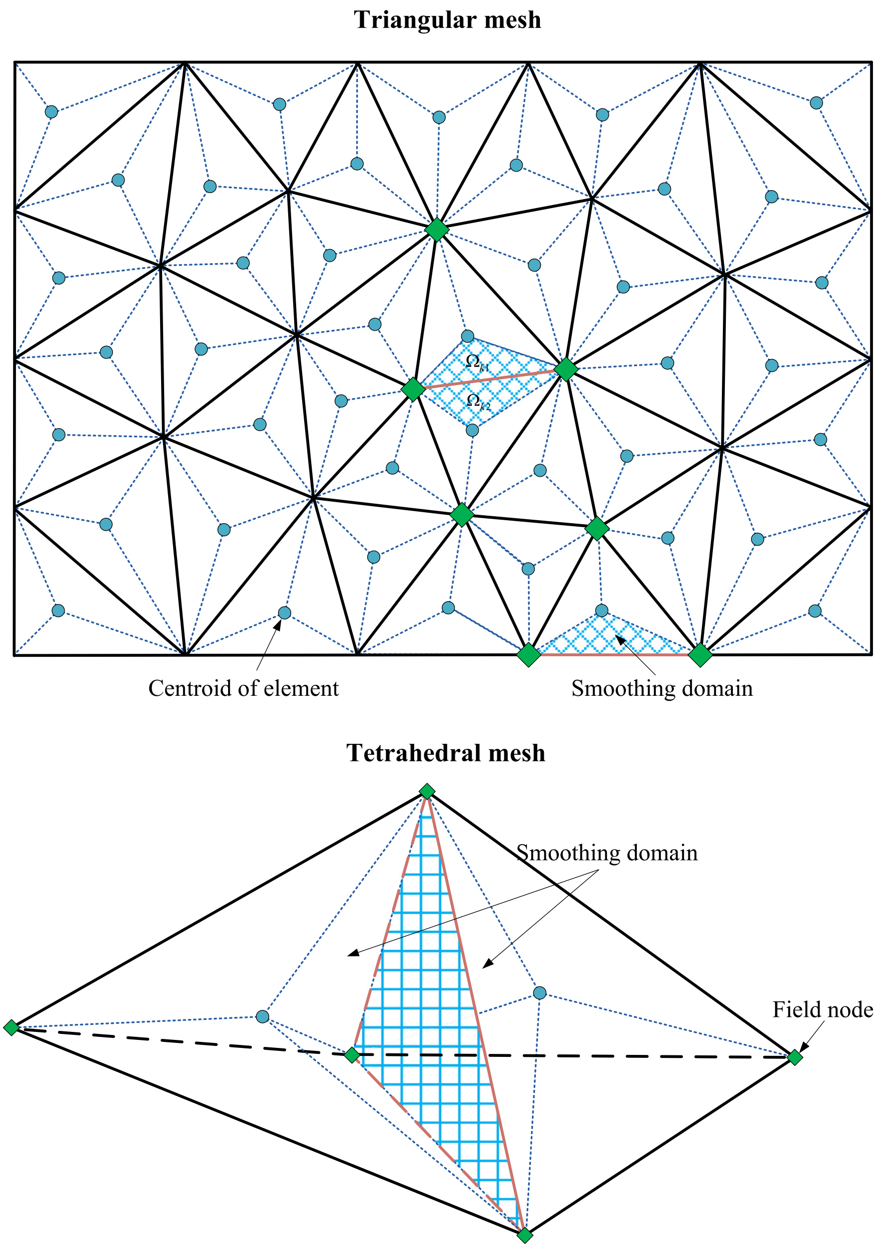

Fig. 1. Construction of edge/face-based smoothing domains.

method [40], combined approximations method (CA) [41–43], etc. For the CA method, terms of binomial series are utilized as high quality basis vectors for the reduced basis expression. Then, accurate global approximations and efficient local approximations are combined to achieve effective solution procedures. The CA method can greatly reduce the computational effort and has been widely utilized for structural design [44]. However, the formulation of CA method is not based on rigorous mathematical proof. The reduced-basis method can effectively avoid this problem, which is obtained through rigorous theoretical proof [45]. Therefore, it has become a powerful model reduction approach which can greatly reduce the computational cost when numerical methods such as FEM, meshfree method are utilized. There are mainly two parts for the reduced-basis method: offline stage and online stage. Full-scale analysis using numerical methods, such as FEM, will be carried out in the offline stage to construct the reduced-basis model. Once such a model is evaluated, the responses of structures for different set of parameters can be calculated rapidly during the online stage and the involved computational cost is significantly reduced compared with that of full-scale forward analysis. This characteristic is the main advantage of reduced-basis method and hence, it can be further combined with inverse analysis to form an efficient algorithm for the design of engineering structures.

The main objective of this study is to build an accurate and efficient algorithm for the optimal design of multi-material structures under thermal loads. The ES-FEM is utilized to obtain the close-to-exact system stiffness and then, the reduced-basis model is constructed based on ES-FEM for the offline stage and the thermal responses of multi-material structures will be rapidly evaluated during the online stage. Finally, the genetic algorithm is used for the inverse analysis to determine the value of design variables, which has been proved to be an effective tool for various engineering optimization problems.

This work is organized as follows. In Section 2, we briefly give the main procedure of ES-FEM for heat transfer analysis. In section 3, the formulation of reduced-basis method is presented and the methodology for coupling this technique with ES-FEM and genetic algorithm is discussed in detail. In section 4, several numerical examples are