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# A novel finite element model updating method based on substructure and response surface model

Deshan Shan *, Qiao Li, Inamullah Khan, Xiaohang Zhou

*Bridge Engineering Department, Southwest Jiaotong University, Chengdu, Sichuan 610031, China*

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ABSTRACT

Combining the substructure finite element model updating method with the response surface model updating method, one novelty finite element model updating method of bridge structure is proposed for updating the finite element model of a certain combined cable-stayed suspension model bridge. In light of specific configurations and mechanical features for combined cable-stayed suspension bridge, substructures are partitioned and the updating design parameters which need to be updated are preselected. On the basis of the variance analysis, the updating parameters are determined by the parameter significance test. Samples of updating parameters are obtained by the homogeneous design method, and the corresponding structural responses are obtained by finite element analysis, finally the response surface model for each updating parameter is fitted and verified. The jointed objective function with the linear combination of fitness functions based on the natural frequency and the static displacement are introduced, and experimental data of the static and dynamic testing for the model bridge is adopted to update the design parameters by the genetic algorithm, then the minimization of the discrepancies between the measurements and the finite element model updating results are achieved. The experimental results show that the updated parameters obtained from the proposed method are reasonable and having a clear physical meaning, and the finite element model of bridge structure can be updated effectively by the proposed finite element model updating method.



## 1. Introduction

It is indispensable to found the accurate finite element model of bridge structure for structural system identification, damage detection and load capacity assessment of real bridge structures [1]. But the results of numerical simulation are generally inconsistent with the measured structural behavior for the reason of material property randomness, construction deviation, structural degradation or damage and some other factors [2].

Material properties, boundary constraints, field measurements, etc. are the main reasons for the discrepancy between the structural response from the Finite Element Model and measured structural response, and quantification of these uncertainties is infeasible in term of large complex structure, such as bridge structure [3,4].

Many finite element model updating methods based on optimization algorithm have been put forward to make the finite element model consistent with structural behavior measurements [5]. Among the optimization-based model updating methods, there are mainly two categories, one is sensitivity-analysis-based (SA-based) algorithm and the other is variance-analysis-based (VA-based) algorithm.

In SA-based finite element model updating methods, the measured structural responses are regarded as the perturbations of design data about the original finite-element mode [5]. By calculating the relationship between the parameters and structural properties, the sensitivity of the parameters can be obtained [5]. Combining the sensitivity-based finite element model updating method with uncertainty analysis, the finite element model of a seven-story reinforced concrete wall building structure is updated by Moaveni et al. [6]; the finite element model of a certain concrete-filled steel tubular arch bridge is updated by Jaishi et al. [7] based on sensitivity analysis; the first-order Taylor-series expansion of the eigenvalues are applied to improve the sensitivity-based updating approach by Zhang et al. [8], and the proposed method is verified by updating a 1/150 scaled suspension bridge; The modal flexibility are adopted as the objective function, then the sensitivity-based method is employed by Jaishi et al. [9] to update the finite element model of a reinforced concrete beam; combining the sensitivity analysis with the two-levels neural network, Lu et al. [10] improve the SA-based finite element model

* Corresponding author. Tel.: +86 13608029847.
*E-mail address:* dsshan@home.swjtu.edu.cn (D. Shan).

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updating method, and a numerical case study is engaged to verify the proposed algorithm.

Based on the statistical analysis of the uncertainties of the structure and measurement, the VA-based model updated algorithm also has a wide range of applications [5]. As the commonly adopted VA-based finite element model updating method, response surface (RS) based finite element model updating method are getting more and more attention in the bridge engineering community [2]. The static [11] and dynamic [12] responses are adopted as the objective function, then the response surface method is adopted by Ren et al. to update the finite element model of Hong Tang Bridge; the finite element model of Tarmar Bridge is updated by Cross et al. [13], aided by RS-based model updating method, and the updated finite element model is adopted to analyze its long-term monitoring data; the RS model updating method based on the radial basis function is applied to update one cable-stayed model bridge by Zhou et al. [14]; combining the RS model updating method with genetic algorithm, the finite element model of one model bridge is updated by Deng [15]; utilizing the measured natural frequencies and mode shapes, RS-based method is adopted by Li et al. [16], to update the finite element model of a certain concrete-filled steel tubular arch bridge, and the updated model is used to predict the structural seismic response.

SA-based algorithms are generally computationally intensive, and it is difficult to converge for the reason of iteration determination of local gradient [12]. Many different approaches are proposed to decrease the computational requirement and improve the converge problem of SA-based algorithms [17,18], and satisfactory results have been achieved. On the other hand, in the VA-based algorithms, the relationship between preselected input and output parameters of the finite element model are carried out in light of the variance analysis of the preselected parameters, and the relationship shown in a mathematical expression, such as polynomial function, is considered as a surrogate model for the finite element model, then the parameters of the surrogate model is updated directly by the measured data [19].

As for as the complex structures are concerned, such as combined cable-stayed suspension bridge, the introduction of substructures can improve the computational efficiency of the model updating [5]. One of the most popular and sophisticated method in dealing with the dynamic analysis of substructure is the component mode synthesis (CMS). It is commonly adopted in the mechanical analysis of large and complex structure which includes the finite element model updating. The finite element model of a bowstring arch bridge is updated by Liu et al. [20,21]. Based on the CMS technique; using a high fidelity model and simulated measurements of a highway bridge, model updating and damage identification applications of CMS technique are demonstrated by Papadimitriou et al. [22]; utilizing the long-term monitoring data from Dowling Hall Bridge, the substructure model updating method are adopted to update its finite element model by Moabeni et al. [23]; substructure finite element updating method is discussed in detail by Weng et al. [24], from the viewpoint of sensitivity analysis; combination the substructure-based model updating method with the artificial neural network algorithm of radial basis function, the finite element model of a certain cable-stayed bridge with single pylon and double cable-plane is updated by Ding [25] and Shan et al. [26], respectively. All of the above mentioned substructure-based finite element model updating belong to sensitivity analysis based model updating methods. Furthermore, there are some additional requirements in the CMS technique based method, such as the coordination transform between the physical coordination and the mode coordination, and different boundary conditions between components [20,22], and some extra skills are required to obtain the satisfactory results [27].

Based on the existed research of finite element model updating methods for bridge structure, and in light of the VA-based finite element model updating method [5], one novel finite element model updating method, which combined the substructure model updating method with RS-based model updating method, is proposed in this paper to update the finite element model of a certain combined cable-stayed suspension model bridge.

## 2. Finite element model updating

The substructure-based finite element model updating method is an effective method for large and complex structural finite element model updating [5]. Based on the sensitivity analysis of design parameters, the design parameter is supposed to be a constant in each substructure in light of the substructure-based model updating method [5], thus it means that the design parameters are updated by regions. However, it is not feasible to achieve the global optimization [5] for the sake of intensive computational effort in practical applications.

Based on variance analysis of uncertainties for design parameters, possible values of design parameters within reasonable limits are determined at first by adopting the response surface model updating method [12,3,11,15], and the possible values of design parameters are termed as the sample points, then corresponding structural responses to all of the sample points are figured out by initial finite element model. Furthermore, regression analysis [28] is utilized to fit the structural responses corresponding to predetermined sample points, and the response surface model of bridge structure to predict the structural response is obtained. Moreover, the fitted response surface model is regarded as a surrogate model of the finite element model in the subsequent process of the design parameters updating. It means that the fitted response surface model of bridge structure is a kind meta-model of structural finite element model in nature [5]. In comparison with the SA-based design parameters updating methods, the parameter significance obtained by VA-based response surface model updating method owns the global property. When the response surface model updating method is applied to the finite element model updating of large and complex structures, the required number of sample points will be increased significantly along with the increasing number of design parameters, and therefore it is difficult to obtain the rational response surface model [5].

Based on the design parameters of finite element model updating theory, a novel finite element model updating approach, which combines the substructure-based model updating with the response surface model updating method, is proposed to update the finite element model of a certain combined cable-stayed suspension bridge. The flowchart of the proposed method is shown in Fig. 1. As shown in this figure, substructure partition, test design, significance test, fitting and validation of response surface function are the keys features of the proposed finite element model method.

### 2.1. Substructure partition

During the finite element model updating, structures can be partitioned into groups of components that are called substructures to improve the computational efficiency [29,30]. For bridge structure, it can be partitioned into substructures in a variety of forms, but the reasonable substructure partition has a direct impact on the efficiency and accuracy of the analysis results. According to the structural and mechanical characteristics of bridge structure and the design parameter based model updating theory [5], the substructure partition is implemented in the light of principles and methods shown in [31].