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Multi-level damage identification with response reconstruction

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ABSTRACT

Damage identification through finite element (FE) model updating usually forms an inverse problem. Solving the inverse identification problem for complex civil structures is very challenging since the dimension of potential damage parameters in a complex civil structure is often very large. Aside from enormous computation efforts needed in iterative updating, the ill-condition and non-global identifiability features of the inverse problem probably hinder the realization of model updating based damage identification for large civil structures. Following a divide-and-conquer strategy, a multi-level damage identification method is proposed in this paper. The entire structure is decomposed into several manageable substructures and each substructure is further condensed as a macro element using the component mode synthesis (CMS) technique. The damage identification is performed at two levels: the first is at macro element level to locate the potentially damaged region and the second is over the suspicious substructures to further locate as well as quantify the damage severity. In each level's identification, the damage searching space over which model updating is performed is notably narrowed down, not only reducing the computation amount but also increasing the damage identifiability. Besides, the Kalman filter-based response reconstruction is performed at the second level to reconstruct the response of the suspicious substructure for exact damage quantification. Numerical studies and laboratory tests are both conducted on a simply supported overhanging steel beam for conceptual verification. The results demonstrate that the proposed multi-level damage identification via response reconstruction does improve the identification accuracy of damage localization and quantization considerably.

1. Introduction

Accurate evaluation of the effect of possible damage in key components is of critical importance in routine operation and maintenance for civil structures. The FE model updating method, as a kind of model dependent method, has drawn a significant amount of research attention during past decades due to its capacity of not only detecting damage existence but also quantifying damage extent. In this kind of method, damage parameter in the FE model is sought through model updating by minimizing the discrepancy between the measured features of the structure in damage and the analytical features predicted by the FE model. The structural damage can then be localized and quantified through solving the inverse problem. However, it can be very difficult to apply this kind method to complex civil structures, in which the difficulties are twofold. On one hand, the 'point' measurements captured by the installed sensors are always limited since the number of sensors is usually restrictedly deployed due to economic constraint; however, the position of damage in a real-world structure cannot be

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known a priori. On the other hand, the dimension of damage searching space is very large owing to the numerous structural components constituting the complex civil structure. Direct seeking the damage vector over the large potential damage space is difficult, if not impossible, to achieve because of numerical difficulty in convergence and enormous computational demand. For the former issue, the demand may be possibly fulfilled through the implementation of response reconstruction, which is to reconstruct the desired responses of the locations where no sensors are installed through the use of measurement data captured by the limited sensors. Dynamic response reconstruction of a structure can be performed using transmissibility based methods [1,2], empirical mode decomposition (EMD) based methods [3,4], Kalman filter based methods [5–8] and others [9]. For the latter issue, it would be advantageous to adopt a substructuring technique following a divide-and-conquer manner: to divide the complex structure into manageable substructures and to perform damage identification on substructures.

Dynamic substructuring technique or specifically CMS method was developed in the 1970s to analyze and design complex structures by decomposing a global structure into a series of smaller substructures in an efficient way [10,11]. Jensen et al. [12] gave a comprehensive and sound review on this topic. As for damage detection using model updating strategy, Weng et al. [13,14] proposed a substructure based FE model updating method performed in the frequency domain for damage identification. The computational demand was dramatically reduced since only concerned substructures and the eigenequation of the condensed structure are re-analyzed in updating procedure. Liu et al. [15] combined the CMS technique with Kriging predictor in the model updating of a complex structure using eigenvalues of the structure. Updating the FE model of an arch bridge was investigated to demonstrate the effectiveness of the proposed method. Chen et al. [16] applied free-interface modal synthesis method to substructure sensitivity based damage detection. Simulation study of an 11-storey frame structure indicated that the substructure based method could detect the damage with a better speed and stability in multi-damage cases. Papadimitriou et al. [17] integrated CMS technique as an efficient model reduction technique into Bayesian FE updating using modal characteristics to alleviate the computation burden involved in the damage identification of a highway bridge. A similar strategy was also reported in reference [18] in Bayesian FE updating using dynamic response data. Shan [19] introduced one novel FE model updating method for bridge structures by combining the substructure FE model updating method with the response surface method basing on the natural frequency and the static displacement. In all above mentioned references, the model updating or damage identification is only performed at a substructure level and it is assumed that all components in the substructure suffer the same damage. However, damage could possibly occur inside the substructure but different components of the substructure may bear damage of different extent.

A similar strategy has been reported in the topic of substructural damage/parameter identification. In the realm of substructural identification, the whole structure is divided into substructures with certain one selected as the target substructure for analysis. Usually, it is implicitly assumed that structural degradations only exist inside the selected substructure. A diverse set of methods of the topic have been reported by many researchers. Some researchers have focused on the frequency domain identification in combinations with measured frequency response functions [20] and cross-power spectral densities [21]. Other researchers have paid close attention to time domain parametric identification using an extended Kalman filter [22,23], an autoregressive moving average with exogenous input model [24], response sensitivity based model updating [25], Bayesian methodology [26] or others. In general, these methods focused on damage identification over the isolated substructure. The internal forces associated with the interface degree of freedoms (DOFs) of the isolated substructure are usually treated as another set of external forces applied on the target substructure and how to determine these forces are of most concern in these methods.

As mentioned above, the limited sensors deployed on the civil structure of large size probably cannot provide enough information on identifying local damage in the structure. Besides, identification of abundant unknown parameters involved in damage identification of a complex civil structure is probably unachievable due to its ill-condition nature and difficulty in computational convergence. What is more, the associated computational efforts will increase tremendously as the size of structural system increases. In this study, a multi-level damage identification with response reconstruction method is proposed. Following a divide-and-conquer strategy, a structure of large-scale is decomposed into several manageable substructures and CMS is adopted to reduce each substructure to a macro element. Damage detection is firstly performed at the macro element level to locate the possible damaged region. Then damage identification is further performed over the suspicious substructure to further locate the exactly damaged element and quantify the damage severity. The proposed method exhibits two distinct advantages: (a) the computation demand in iteratively solving the inverse problem is largely decreased and (b) the damage parameter searching dimension is reduced in the damage detection at each level, both making solving the inverse problem achievable and much easier. The remaining section of the study is structured as follows. Firstly, as the solution method of the proposed strategy, ℓ_1 norm regularized model updating is briefly introduced in Section 2. Then the multi-level damage identification is proposed and introduced in Section 3. Section 4 and Section 5 present the numerical studies and laboratory tests on a simply-supported overhanging beam, respectively. Conclusions and future work are finally discussed in Section 6.

2. Response sensitivity based FE model updating

The rationale underlying the response sensitivity based FE model updating for damage identification is to seek the damage parameter (flexural stiffness EI, for example) corresponding to the damaged state by minimizing the discrepancy