論 文 の 内 容 の 要 旨

論文題目　Development of Model Updating in 3D AEM to Improve the Numerical Modeling of Existing RC Frame Buildings (既存RCフレーム建物の数値解析モデルの改善のための3次元応用要素モデルの更新法の開発)

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In the contemporary built environment, a significant proportion of building structures, particularly Reinforced Concrete (RC) frame buildings, face substantial seismic risk, primarily attributed to substandard construction techniques and non-uniform constituent elements. These non-engineered structures lack durability and resilience due to the absence of essential elements such as sufficient capacity, ductile detailing, and construction quality. To understand the structural status of these buildings and mitigate seismic risk, numerical modeling is essential.

Different numerical techniques, the finite element method (FEM) and discrete element methods (DEM) etc., have demonstrated their efficacy in offering precise numerical modeling. However, constructing numerical models involves uncertainties and assumptions. To validate the results, researchers rely on non-destructive measurements and compare them with numerical data. Model update approaches, which modify unknown factors, have been introduced to reduce discrepancies between experimental and numerical dynamic characteristics.

Operational modal analysis techniques like frequency domain decomposition (FDD) or stochastic subspace identification (SSI) can extract mode shapes and modal frequencies from ambient vibration measurements, providing valuable inputs for model updating. Despite the abundance of research on finite element (FE) model updating, there is limited research on model updating for low to mid-rise RC buildings with relatively higher stiffness due to infill masonry. Additionally, the Applied Element Method (AEM) proves to be an accurate approach for monitoring structure response but lacks existing numerical model updating techniques.

The thesis aims to address this research gap by exploring numerical model updating technique for low to mid-rise RC buildings, particularly those analyzed using the Applied Element Method, providing insights to enhance seismic resilience and safety in the face

of actual disasters. There are four specific objectives of this research. The first objective is to develop a least square problem for model updating, tailored to these types of structures. The second objective involves integrating the model updating methodology into 3D AEM numerical modeling. The third objective focuses on enhancing the computational efficiency of the 3D AEM tool. Finally, the research aims to perform a seismic vulnerability assessment of an existing building using vibration data, which will help in evaluating its susceptibility to seismic events.

In this research, first, a least square problem for model updating which is suitable for low to mid rise buildings having limited number of operational modal data and limited measurements is developed. The least square problem is formulated calculating the relative residual vector of experimentally measured modal properties and analytical modal properties. The analytical modal properties are calculated using the initial guess of updating parameters for the model updating which are material properties (Young's Modulus/ stiffnesses) for the numerical model of the structure. Using the formulated least square problem as the objective function for the minimization problem, the problem is solved to get the optimum value of updating parameters using Levenberg-Marquardt algorithm. Initially, the model updating implementation is examined for generalized shear frames with various scenarios involving limited measured degree of freedoms (DOFs) and the no. of modes used for model updating, evaluating the accuracy of stiffness updates for structural systems. From this implementation it is understood that obtaining higher modes in structural analysis becomes challenging and leads to spurious results with increased damping, causing inaccuracies in updating the model. However, it is feasible to update the structural model using a limited number of measured degrees of freedom (DOFs) and modes in operational modal analysis. While frequency parameters can be obtained relatively accurately, mode shape parameters are less precise. In the presence of spurious modes, giving higher weightage to the residual involving eigenvalues is recommended in the model updating process.

Subsequently, the method is tested on a 3-storey scaled experiment model of a steel frame with bolt-connected joints, inducing damage in different locations by loosening the bolting condition. Ambient vibration measurements are taken in one direction on each floor level, and operational modes and frequencies are obtained using frequency domain decomposition. Through model updating, the storey stiffness of the experiment model is accurately determined, enabling identification of the damage caused by loosening bolts at each storey level. Comparisons between the modal properties of the updated structure and the experimental modal properties validate the accuracy of the model updating process.

One of the objectives of this research is to model real existing structure in 3D AEM. So, it was necessary to improve the current solvers and storage systems used in 3D AEM. With the comparison of different solvers and storage system, parallel direct sparse solver (PARDISO) with triplet storage format using multiple thread of CPU is identified to be the most efficient one and is implemented in 3D AEM.

In the next phase, a four-storey reinforced concrete (RC) frame building representing typical buildings in Nepal is utilized for implementing the model updating methodology. Synthetic data of experimental operational mode shapes and frequencies are obtained by applying frequency domain decomposition to the response of the structure subjected to white noise using actual material properties. The 3D AEM is employed to model the structure with unknown stiffnesses, categorized into three groups: beam/slab, column, and infill wall properties, which serve as the updating parameters. The ARPACK-Arnoldi package integrated in 3D AEM is utilized to obtain analytical modal properties, and the least square problem is formulated based on the residual of experimental and analytical modal properties. The Levenberg-Marquardt algorithm is applied to minimize the problem and obtain the updating parameters. Comparisons between the Young's Modulus and modal parameters of the updated structure with the assumed values validate the successful implementation of the model updating in 3D AEM, confirming that acceptable error margins can be achieved through this approach.

Next, static and dynamic analysis of the updated numerical model is performed to understand the seismic vulnerability of the structure using 3D AEM. The quantification of the overall damage and local damages are studied successfully in performance criteria based on interstorey drift, frequency degradation and deformation of the structure. The static pushover analysis of the case study structure indicates soft storey behavior, with displacement concentration on the ground floor. This is evident from the higher inter-storey drift ratio on the ground floor compared to upper floors. Failure patterns observed include in-plane shear cracks, on-plane failure of masonry walls, and tensile failure at beam column joints. The frequency degradation curve shows a reduction in stiffness with increasing lateral displacement. The incremental dynamic analysis of the updated 3D AEM model for various ground motions enhances our understanding of the building's seismic performance, providing valuable information on deformation, damage level, and failure mechanisms. These insights can be utilized to optimize the design of structures and improve earthquake resistance.

Finally, the method is then applied to real existing building structures using ambient vibration data measured from the field and analyzed in 3D AEM. The Young's Modulus (stiffnesses) of the structure is considered unknown and assigned random initial values. The elements are grouped into 11 different groups, including floorwise beams/slabs, columns, shear walls, and infill walls, serving as the updating parameters. Comparisons between the Young's Modulus (stiffnesses) and modal parameters of the updated structure with the actual assumptions validate the successful implementation of the model updating in 3D AEM. The study demonstrates that accurate numerical model updating in 3D AEM is achievable with a limited number of operational modes obtained from the field, but the accuracy heavily depends on the initial guess of the updating parameters. The updated structure is then performed non-linear analysis using static pushover analysis to understand the capacity and performance of the structure.

In conclusion, the least square problem for model updating which is suitable for low to mid rise buildings having limited number of operational modal data and limited measurements is developed and successfully tested for the generalized frame structures. Next, the model updating methodology is successfully integrated in 3D AEM numerical modelling. It is now possible to perform the parameters update for the numerical model for real existing buildings. Also, the computational efficiency of 3D AEM tool is significantly improved with the use of parallelized direct solver (PARDISO), and it is used for performing seismic vulnerability assessment of the real existing building using vibration data using both dynamic and static analysis methods successfully.

The thesis is organized in seven chapters as followings:

Chapter 1: Introduction

Chapter 2: Sensitivity-based model-updating method

Chapter 3: Implementation of the sensitivity-based model-updating for an experimental model.

Chapter 4: 3D AEM integration of the sensitivity-base model updating

Chapter 5: Seismic vulnerability of the updated model structure using 3D AEM

Chapter 6: Implementation of the model updating in real structure

Chapter 7: Conclusion and Future Scope