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RAPID ASSESSMENT OF NON-INSTRUMENTED FLOORS: A REVIEW OF METHODS AND A NEW SIMPLIFIED DIGITAL TWIN APPROACH

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Abstract

This study presents a comprehensive review of three significant methods proposed for Structural Health Monitoring (SHM) systems in high-rise buildings. These methods are evaluated for their effectiveness in estimating the responses of non-instrumented floors, providing crucial insights into building safety. Although each method has its own advantages and limitations, they make important contributions to the literature by enabling rapid assessment of floor responses in monitored buildings. In addition to the reviewed methods, a new simplified digital twin approach is introduced in this study. The knowledge of structural system, material properties, and the first modal periods in three directions (two translational and one torsional) are necessary for constructing a simplified digital twin. The proposed method has been validated through case studies of both a representative frame and a real building, demonstrating that the simplified model accurately represents the periods and mode shapes of the structures. Although the numerical examples are two-dimensional, the method is designed for three-dimensional applications, allowing for the representation of torsional modes. The method's key advantage is that, for structures with regular geometry, knowing only the first modal period in each direction is sufficient for model calibration.

Keywords: Digital Twin, Structural Health Monitoring, Simplified Model, Rapid Assessment

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1 INTRODUCTION

Structural Health Monitoring (SHM) systems aim to detect damage using data obtained from sensors placed on the structure. SHM systems could answer four fundamental questions defined by Rytter [1] to detection of damage: (1) is there any damage in the structure? (2) If there is damage, where is it located? (3)What is the type and level of the damage? (4)What is the remaining service life of the structure? Most of studies on SHM aim to provide accurate and precise answers to these four questions.

Measuring vibration data is the most commonly used method in Structural Health Monitoring (SHM). Katam et al. [2] classified traditional data evaluation methods in vibration-based SHM systems into four categories: time-based, frequency-based, modal-based, and numerical-based methods. The study also covers recent data evaluation techniques such as artificial intelligence, deep learning, and machine learning. In frequency-based methods, dynamic structural characteristics such as frequencies, damping ratios, and mode shapes are estimated. For damage detection, changes in dynamic parameters are used. While changes in these parameters are effective for detecting damage, nevertheless provide limited information about the precise location and extent of the damage. Modal-based methods detect damage using mode shapes and their derivatives. When high-rise buildings considered as a cantilever beam, the first derivative represents rotation, while the second derivative represents curvature of the beam. Modal-based methods provide more detailed information about the location of the damage [3].

Numerical-based methods provide more detailed information about damages in a structure. It is possible to calibrate a numerical model using data from sensors. The calibrated model can be used as a digital twin of the structure. The digital twin is more advantageous in situations where only a limited number of sensors can be used due to high sensor costs, such as in high-rise structures. Numerical-based methods allow the possibility of obtaining information about areas without sensors, providing an offering a broader perspective on structural condition and damage distribution. In these methods, classical 3D Finite Element Models (FEM) calibrated with sensor data are used as digital twins. However, due to the long analysis times of these detailed FEMs, researchers have also developed alternative numerical-based methods that can provide faster assessment results.

In this study, a new approach is introduced where the number of elements is reduced to represent vertical structural elements of the structure. This approach is examined through simple numerical examples. The proposed method aims to reduce analysis times significantly, especially in high-rise buildings.

2 THE METHODS FOR THE ESTIMATION OF NON-INSTRUMENTED FLOOR RESPONSES IN THE LITERATURE

In this section, detailed information is shared about three significant and innovative studies from the literature that focus on determining the responses of non-instrumented floors in monitored buildings and assessing the safety of structures.

2.1 System identification and model calibration of multistory buildings through estimation of vibration time histories at non-instrumented floors.

Kaya et al. [4] have proposed a new method called "Mode Shape Based Estimation (MBSE)" to determine the structural responses of non-instrumented floors. This method argues that each mode shape of building-type structures is a linear combination of bending and shear beams. Figure 1 shows the mode shapes of bending and shear beams for the first six modes. The coefficients required for the linear combination of mode shapes are determined using data from the instrumented floors.

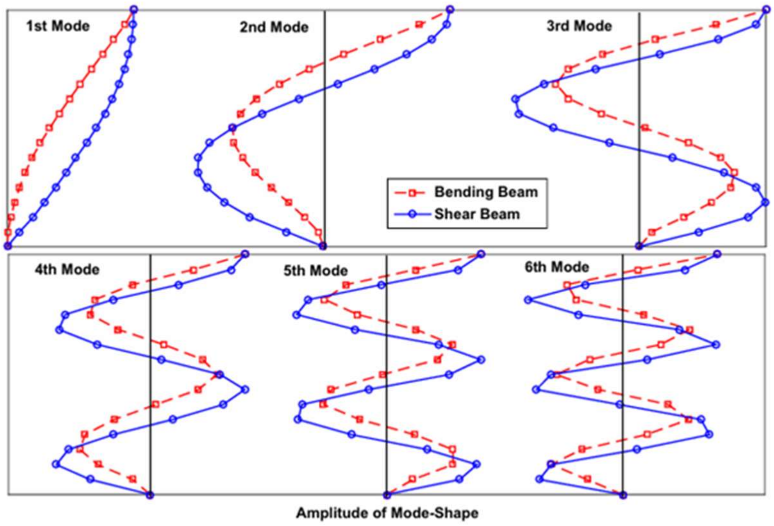

Figure 1 Mode shapes for the first six modes of shear and bending beams [4].

Data from UCLA's Doris and Louis Factor building, a 17-story structure, were used to validate the method. Since each floor of the building is instrumented, it is highly suitable for validating the method. Using data from only three floors (the 1st floor, 6th or 8th floor, and the roof), the MBSE method was applied to predict the mode shapes and acceleration-time histories of the other floors. The model was accordingly validated with the recorded data. Figure 2 shows the comparison between the mode shapes determined by the MBSE method and the actual mode shapes. Additionally, the results are compared with conventional methods such as linear and spline interpolation. In Figure 3, the acceleration time histories for the 13th floor during the West Hollywood (Oct. 30, 2004, Mw 2.7) earthquake are presented, obtained using the MBSE method, as well as linear and spline interpolation methods. As seen from this graph, the MBSE method provides significantly better results compared to linear and spline interpolation. As a drawback of this method, it can be noted that torsional modes are disregarded.

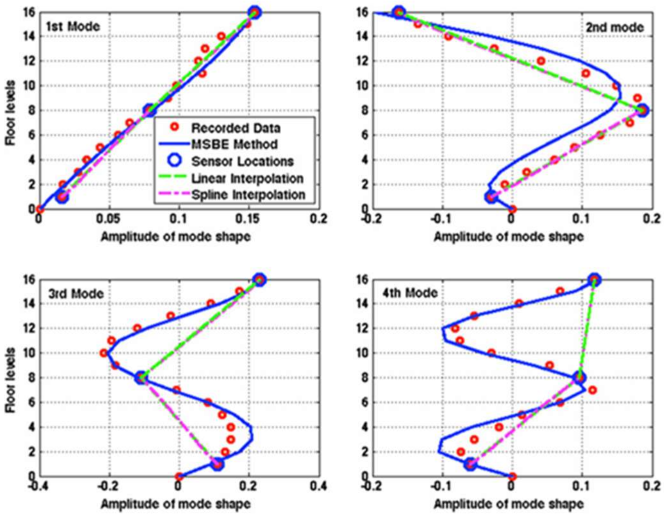

Figure 2 Determination of mode shapes for the UCLA building using the MBSE method, linear and spline interpolation with data from the 1st, 8th, and roof floors, and comparison with measurement data. [4]

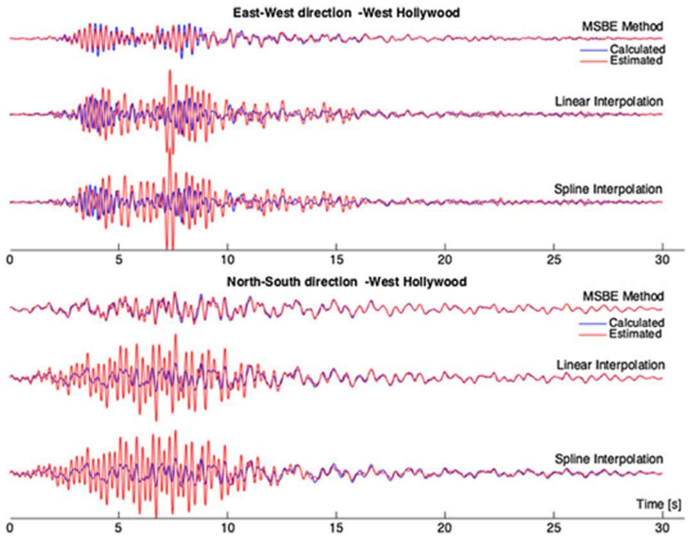

Figure 3 Comparison of real acceleration and acceleration-time histories obtained by MBSE method, linear and spline interpolation for the 13th floor during the West Hollywood earthquake. [4]

2.2 Structural condition assessment with structural health monitoring systems and non-linear simplified models.

Aytulun and Soyöz [5] proposed the Nonlinear Simplified Model (NLSM) method to determine the response of non-instrumented floors. This approach models the structure for each floor using flexural springs and nonlinear shear springs. The most notable feature of this study is its ability to predict the structure's response after damage occurs, considering the nonlinear behavior. Figure 4 shows the process for determining the shear and flexural spring values. Here, the values of the shear and flexural springs are mathematically related to each other. This relationship is based on the study conducted by Boutin et al. [6] The graph presented in Figure 5 expresses the formulation that allows for determining the C coefficient based on the ratio of the desired frequency to the first natural frequency in that direction. Depending on the F_i/F_1 ratio, the C coefficient is determined for both directions, and this coefficient defines the relationship between the flexural and shear springs. After the C coefficient is determined, the procedure given in Figure 4 is followed to calculate the stiffness of the elastic shear and flexural springs.

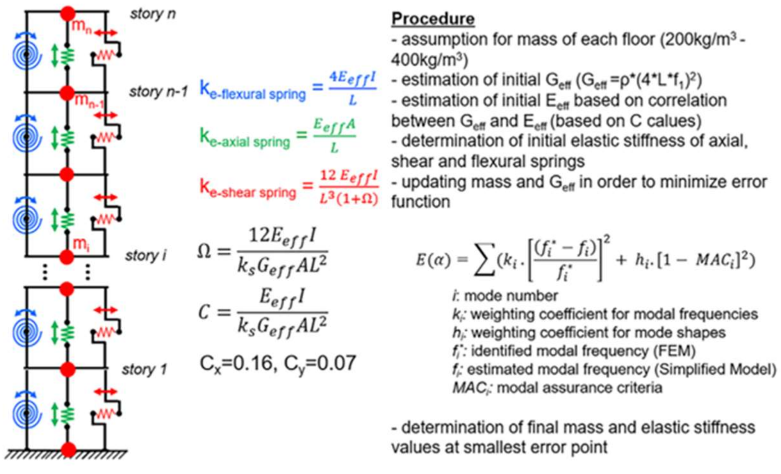

Figure 4 Procedure for Nonlinear Simplified Model (NLSM) method. [5]

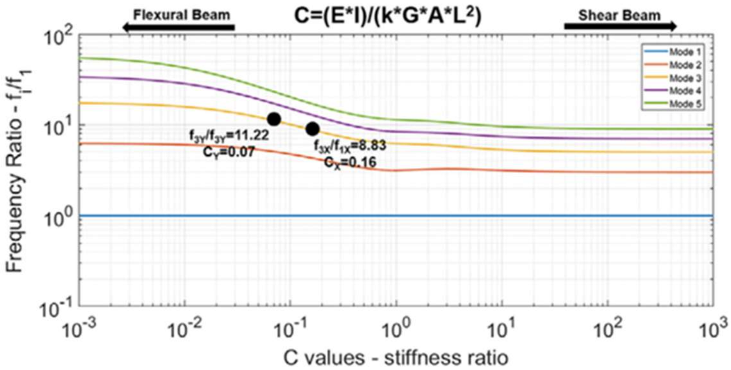

Figure 5 C coefficient for the flexural beam and shear beam. [5]

, Unscented Kalman Filter and Simulated Annealing methods were used to determine the post-elastic behavior of springs. In the final part of the study, the method was applied to a 7-story reinforced concrete Van Nuys building that was damaged in the 1994 Northridge earthquake. The method yielded highly successful results in predicting mode shapes and time series.

The biggest advantage of this method is that it can also represent nonlinear behavior. However, the effects of torsional modes have been neglected.

2.3 Model updating and seismic response of a super tall building in Shanghai.

In the study conducted by Pan et al. [7], the seismic response of the Shanghai Tower is determined using the results of the Operational Modal Analysis (OMA). To perform rapid analyses, a simplified version of the detailed 3D model, referred to as the "Baseline Finite Element Model," was created. In the development of the Baseline FEM, the principles from the study by Liu et al. [8] titled "Lumped-Mass Stick Modeling of Building Structures with Mixed Wall-Column Components" were applied. The expression in Equation 1 shows that the horizontal stiffness is represented as the sum of the stiffness of the elements in that direction. The term $\emptyset_{xj}$ accounts for the effects of shear deformations. The torsional stiffness is defined in Equation 2 as the stiffness of each vertical structural member multiplied by the square of its distance to the center of torsion. By combining all these stiffness into a single stick element for each floor, the Baseline FEM is constructed.

$$k_x = \sum_j k_{xj} = \sum_j \frac{12EI_{yj}}{H^3(1+\emptyset_{xj})} \tag{1}$$

$$k_z = \sum_j [\, k_{xj}\,(y_j - y_s)^2 + \, k_{yj}(x_j - x_s)^2] \tag{2}$$

The results of the baseline model developed for the Shanghai Tower were compared with the results of a detailed ABAQUS model. According to the results presented in Figure 6, the baseline FEM and the ABAQUS model provided consistent results under seismic motions.

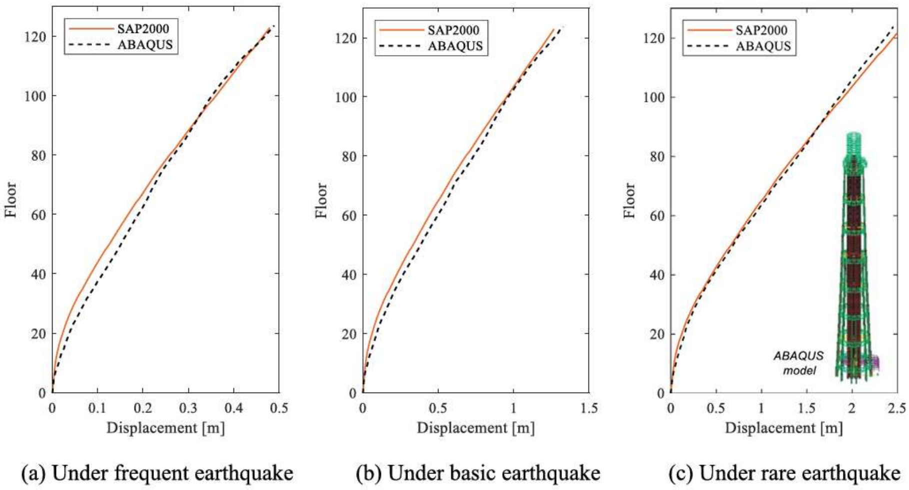

Figure 6 comparison of max story displacement results between the baseline FEM and the ABAQUS model [7]

3 THE PROPOSED SIMPLIFIED DIGITAL TWIN APPROACH FOR ESTIMATION OF NON-INSTRUMENTED FLOOR RESPONSES

As detailed in the literature review in Section 2, the behavior of a structure can be modeled as a combination of a bending beam and a shear beam. While the shear walls behave like bending beams, the column-beam frames exhibit shear beam behavior. In this study, a simplified finite element model (FEM) is planned by reducing the number of nodes and elements, taking these behavior effects into account.

In this section, the working principles of the proposed new method will be examined using two-dimensional structures, and in future studies, its applicability to three-dimensional structures will be investigated. The total horizontal inertia of the vertical structural elements in the structure will be represented by at least two representative vertical elements. The connection between these two vertical elements will be achieved through a fictitious beam. In a structure with a completely regular frame system, the total inertia of the vertical elements can be divided into two equal parts and represented by two vertical elements. For a structural system consisting of both shear walls and frame columns, the shear-wall inertia will be assigned to one vertical element, while the sum of column inertia will be assigned to the other vertical element. Depending on the configuration of the frame system, the number of vertical elements may increase, but it is essential to keep the number of elements as low as possible

The stiffness of the fictitious beam (I_B) between the representative vertical elements is adjustable. When its stiffness approaches zero, the simplified model behaves like a bending beam, whereas if the stiffness approaches infinity, it exhibits shear beam behavior, Figure 7 and 8. When the stiffness of the fictitious beam is adjusted so that the first modal period of the simplified model matches the value obtained from Structural Health Monitoring (SHM) data, the other modal frequencies and mode shapes will automatically align as well.

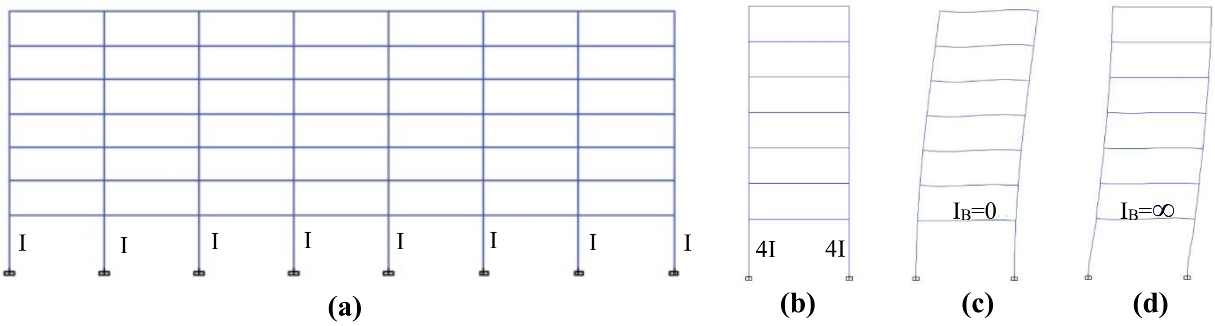

Figure 7 Creation of the simplified model and the effect of fictitious beam stiffness: (a) 2D plane frame, (b) simplified model of the plane frame, (c) first mode shape of the simplified model when the stiffness of the fictitious beam approaches zero, (d) first mode shape of the simplified model when the stiffness of the fictitious beam approaches infinity.

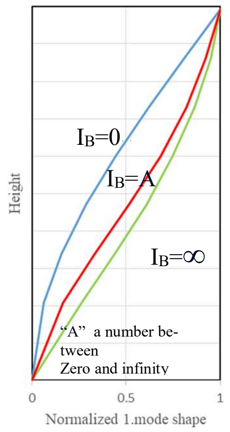

Figure 8 First mode shape of the simplified model for different values of fictitious beam stiffness, illustrating the transition between shear beam and bending beam behavior.

3.1 Numerical example

In this example, a 2D frame consisting of shear walls and columns has been simplified using the methodology described above. The inertia of the shear walls is summed up in one vertical frame element, while the stiffness of the columns is summed up in another vertical frame element. A fictitious beam has been defined between the two representatives vertical frame elements, as shown in Figure 9. The moment of inertia of the fictitious beam has been increased until the first period values of the detailed model and the simplified model coincide. When the first period values of both models match, the other period values and mode shapes yield results with an acceptable level of proximity, as shown in Figure 10. In both models, rigid diaphragm assumptions have been made at each floor. In the simplified model, the total floor mass has been equally divided between two points on that floor.

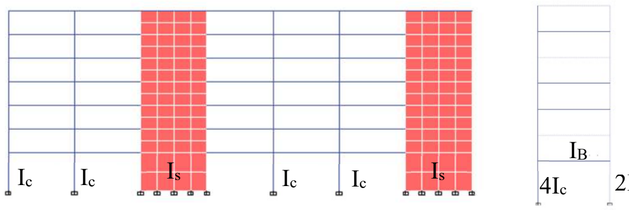

Figure 9: Numerical example: (a) 2d-detailed frame model, (b) simplified model

Mode	Detailed Model Period (s)	Simplified Model Period (s)
1	1.21	1.22
2	0.26	0.26
3	0.12	0.14

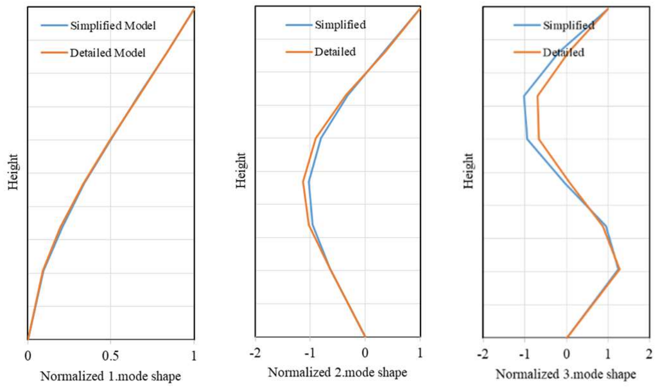

Figure 10: Comparison of numerical example modal analyze results between detailed and simplified model

3.2 Real word example

The Van Nuys building holds a significant place in SHM literature. Constructed in 1966, this 7-story reinforced concrete frame structure has a wealth of earthquake data available, which can be accessed through https://www.strongmotioncenter.org/. The structural health monitoring system in the building is provided in Figure 11. The building sustained damage during the 1994 Northridge earthquake. Extensive research has been conducted on the damage incurred and the post-earthquake field studies related to the structure. [9]

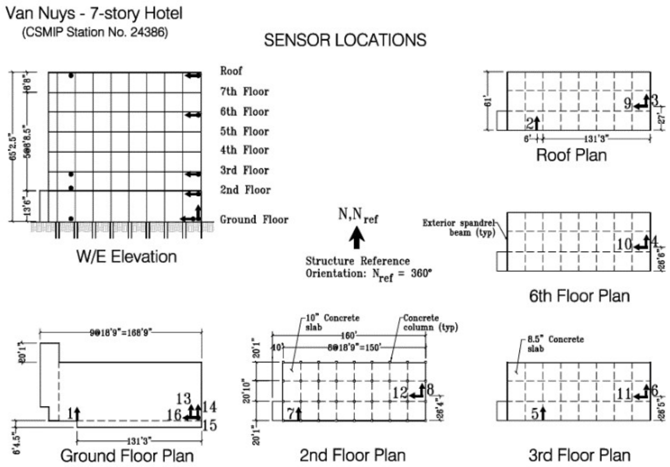

Figure 11: SHM system of Van Nuys -7- story hotel (from CGS - CSMIP Station 24386)

In this part of the study, using the data from the 1987 Whittier earthquake, the modal periods and mode shapes of the building in the EW direction were obtained. The first mode of the structure in the EW direction has been determined to be 1.14 seconds, Figure 12. In a study conducted by Shan et al. [10], the same value for the first mode was found. The concrete classes of the structural elements in the building were taken from the study by Gicev and Trifunac [11]. The column dimensions related to the structural system of the building were obtained from the peer report titled Van Nuys Hotel Building Testbed Report: Exercising Seismic Performance Assessment (2005/11). [12]

In the simplified model, the total moment of inertia of the columns was calculated and divided into two equal parts, represented by two vertical elements. Between the two vertical elements, fictitious beams were defined at the level of the floor slabs. The stiffness of these fictitious beams was adjusted until the first modal period of the simplified model converged to

1.14 seconds. When the first period values overlapped, the other period values and mode shapes also showed the desired consistency, Figure 13.

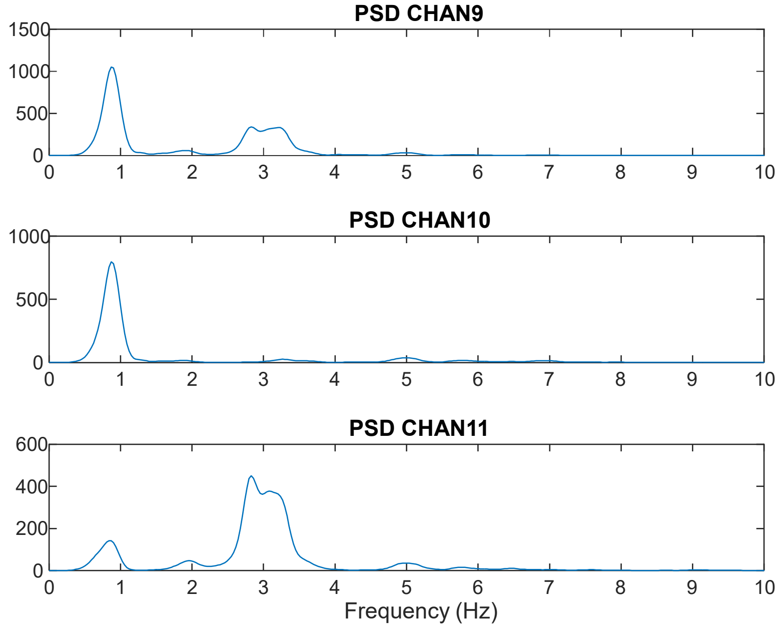

Figure 12: Determination of dominant frequencies of the structure in the EW direction using the Welch method.

Mode EW	SHM Period (s)	Simplified Model Period (s)
1	1.14	1.18
2	0.35	0.38
3	0.20	0.21

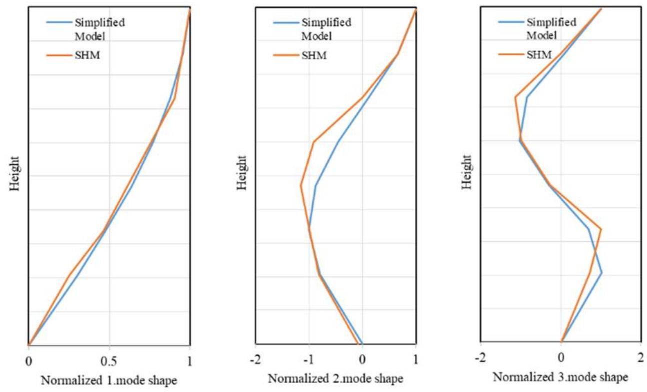

Figure 13: Comparison of modal analyses results between detailed and simplified model of Van Nuys Building

4 CONCLUSIONS

In this study, three important methods for use in structural health monitoring systems in high-rise buildings have been thoroughly examined through a review of the literature. While each of these three methods has its own advantages and disadvantages, they have made significant contributions to the literature, particularly in terms of quickly determining the responses of floors without sensors.

In addition to these three methods, a new simplified digital twin method is introduced in this study. According to this method, in order to create a simplified digital twin of a structure, it is necessary to know the structural system, material properties, and the first modal periods in three directions (two horizontal translational and one torsional around vertical).

To validate the method, one representative frame and one real building was used. The results indicate that the simplified digital twin successfully represents the periods and mode shapes of the structures. Although the examples in this study were designed in two dimensions, the method allows three-dimensional analysis including torsional movements. Furthermore, the method's potential strength is that knowing only the first modal period in each direction is sufficient for calibrating the simplified model.

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REFERENCES

[1] Rytter, A. Vibrational Based Inspection of Civil Engineering Structures. Dept. of Building Technology and Structural Engineering, Aalborg University, 1993.

[2] R. Katam, P. Kalapatapu, V. D. K. Pasupuleti. Smart Diagnosis of a Cantilever Beam Using SVM. 2023 International Conference on Emerging Techniques in Computational Intelligence (ICETCI). Hyderabad, India, 2023, pp. 27-32.

[3] N. M. M. Maia, J. M. M. Silva, E. A. M. Almas, R. P. C. Sampaio. Damage Detection in Structures: From Mode Shape to Frequency Response Function Methods. Mechanical Systems and Signal Processing, 17(3), 2003, pp. 489–498. doi:10.1006/mssp.2002.1506.

[4] Kaya Y., Kocakaplan S., Şafak E. System Identification and Model Calibration of Multi-Story Buildings Through Estimation of Vibration Time Histories at Non-Instrumented Floors. Bulletin of Earthquake Engineering, 13, 2015, pp. 3301–3323.

[5] E. Aytulun, S. Soyöz. Structural Condition Assessment with Structural Health Monitoring Systems and Nonlinear Simplified Models. Earthquake Engineering & Structural Dynamics, First published: 17 April 2024. doi:10.1002/eqe.4132.

[6] C. Boutin, S. Hans, E. Ibraim, P. Roussillon. In Situ Experiments and Seismic Analysis of Existing Buildings. Part II: Seismic Integrity Threshold. Earthquake Engineering & Structural Dynamics, First published: 01 June 2005. doi:10.1002/eqe.503.

[7] Y. Pan, C. E. Ventura, H. Xiong, F.-L. Zhang. Model Updating and Seismic Response of a Super Tall Building in Shanghai. Computers & Structures, 239, 15 October 2020, 106285. doi:10.1016/j.compstruc.2020.106285.

[8] Y. Liu, R. Chen, Y. Jiang, W. Liu. Lumped-Mass Stick Modeling of Building Structures with Mixed Wall-Column Components. 15th World Conference on Earthquake Engineering (15WCEE), Lisbon, 2012.

[9] S. S. Ivanović, M. D. Trifunac, E. I. Novikova, A. A. Gladkov, M. I. Todorovska. Ambient Vibration Tests of a Seven-Story Reinforced Concrete Building in Van Nuys, California, Damaged by the 1994 Northridge Earthquake. Soil Dynamics and Earthquake Engineering, 19, 2000, pp. 391–411.

[10] J. Shan, L. Wang, C. N. Loong, Z. Zhou. Rapid Seismic Performance Evaluation of Existing Frame Structures Using Equivalent SDOF Modeling and Prior Dynamic Testing. Journal of Civil Structural Health Monitoring, 13, 2023, pp. 749–766. doi:10.1007/s13349-023-00677-6.

[11] V. Gicev, M. D. Trifunac. Non-Linear Earthquake Waves in Seven-Storey Reinforced Concrete Hotel. Report CE 06-03, Department of Civil Engineering, University of Southern California, Los Angeles, California, November 2006.

[12] H. Krawinkler (Ed.). Van Nuys Hotel Building Testbed Report: Exercising Seismic Performance Assessment. PEER Report 2005/11, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, October 2005.