UNCOUPLED MODAL RESPONSE HISTORY ANALYSIS USING MODAL PUSHOVER ANALYSIS-BASED RESPONSES

Jirapat Watchawong[1,*] and Pennung Warnitchai[1]
[1] *Asian Institute of Technology, Pathum Thani, Thailand*

*Corresponding author: jirapat.watchawong@gmail.com

1. INTRODUCTION

The evaluation of the seismic response of buildings, particularly high-rise structures, is one of the most important tasks in civil engineering and structural design. The nonlinear behavior of structures under seismic loads presents a complex problem that requires accurate and efficient analysis methods. Traditional methods like Nonlinear Response History Analysis (NLRHA) have been considered to be the most reliable method for designing of new building or evaluating of existing building. However, due to the complexity of nonlinear properties of structure, NLRHA are known for their computational intensity and significant time consumption [1].

In the development of a catastrophe model that can evaluate seismic losses and impacts of the specific area, it becomes necessary to analyze buildings using various series, magnitudes, and mechanisms of ground motions. The NLRHA method is not suitable for this task due to its computation time issue. In recent years, the need for faster and simplified methods has led to the development of alternative methods such as Uncoupled Modal Response History Analysis (UMRHA). UMRHA uses the concept of superposition of nonlinear single-degree-of-freedom (SDOF) systems [2], which significantly reduces the computation time compared to NLRHA.

Moreover, the ability of UMRHA to extract the complex nonlinear seismic response has been used to investigate the problem of using the reduction factor (R) in response spectrum analysis (RSA). Several studies using UMRHA have shown that different vibration modes exhibit different degrees of nonlinearity under the same ground motion. Using the same R-factor for every mode leads to an underestimation of the force demand from higher mode [1], [3]. This confirms that the ability of UMRHA to accurately estimate the demand of each mode is very beneficial and can be used in many applications.

Since, the UMRHA has been shown in previous studies to be effective in estimating global responses (e.g., base shear and roof displacement) as well as story-level responses (e.g., story drift, story shear, and story moment) when compared to the results obtained from the NLRHA. However, the accuracy of the UMRHA in predicting component-level demands (e.g., force in each column and force in each wall) is questionable due to the assumption that the force distribution pattern of each individual component will remain constant, which is only valid when the structure is responding within the elastic limit. Once nonlinear behavior occurs, the lateral stiffness of the damaged component will decrease, causing lateral forces to distribute more towards undamaged components. Therefore, the constant force ratio assumption used in previous studies will underestimate force demand in undamaged components [4].

The key solution for addressing component-level demands is to introduce a new technique for estimating the component-level response of UMRHA. In this study, two sets of data from different analysis procedures are required: the time history of roof displacement from the UMRHA procedure and the force demand from modal pushover analysis. The core concept of this proposed technique involves cross-mapping the roof displacement from both analyses. The time history of roof displacement from UMRHA is used to select the force demand from the modal pushover analysis, this selected force demand from the modal pushover analysis is then used as a force demand for the UMRHA procedure.

Another limitation of the current UMRHA is the idealization of the hysteretic model for the SDOF system. Most hysteretic models were developed based on symmetric backbone curves. However, real buildings are often irregular, and their actual hysteretic behavior is unsymmetrical. Therefore, using a symmetric hysteretic model would only capture the response of one side of the structure. Kam et al. [5] proposed the idea of creating new hysteretic models by combining different existing models. In their study, a bilinear flag-shaped hysteretic model was created by combining a bi-linear elastic model with a bi-linear elastoplastic model. This approach provides a convenient way to create new suitable hysteretic models from existing ones without starting from scratch. This is very convenient for practical applications, since it is not necessary to write a software script for a new hysteretic model.

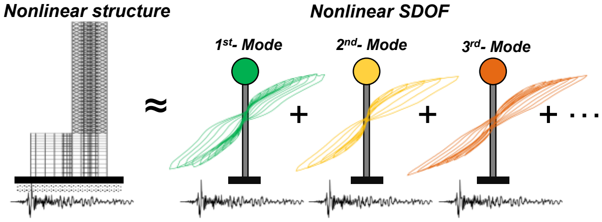

Figure 1. The basic concept of UMRHA procedure

2. METHODOLOGY

To develop a technique for accurately predicting component-level responses, this study proposes a new approach that involves mapping between two different analysis procedures: UMRHA and Modal Pushover Analysis (MPA). The concept of this technique is that both UMRHA and MPA use the same lateral force pattern to push the structure, so the force demands from both analyses are approximately identical to each other. Therefore, the force demand from monotonic MPA can be used as the force demands for UMRHA.

This technique relies on using the global response of UMRHA, which is the roof displacement results obtained from the time history analysis of an idealized SDOF system. Roof displacement results from UMRHA will be used to select the demand from monotonic MPA through the response mapping technique. For every time step, the force demand from monotonic MPA is chosen based on the corresponding roof displacement result of UMRHA. This process must be conducted separately for each mode, and the demands from each mode are then combined throughout the time history later. Once this process is completed, the envelope of force demand can be generated by finding the maximum value over the time history.

To accurately determine the force demand for each component using this technique, it is essential to pre-record the force demand for each component at every incremental loading step. Utilizing a smaller loading step size will enhance the precision of the mapping process. Additionally, due to the irregularity of the building, it is necessary to conduct a modal pushover analysis in both positive and negative directions. After all the necessary data (including the force demand of each component and its corresponding roof displacement values) are well-prepared, MATLAB software is used to perform the mapping and combine the responses. Finally, the peak envelope of force demand for each structural member is computed.

To address the discrepancy between actual hysteretic behavior and idealized behavior, this study introduces a new hysteretic model with an unsymmetrical backbone curve. The proposed Multi-Linear Flag Shape (MLFS) hysteretic model consists of five linear segments on each side and includes residual deformation, allowing for a more suitable idealization. The proposed MLFS model was developed in OpenSees software through a combination of Multi-Linear material and Elastic Perfectly Plastic (EPP) material, as shown in Figure 3. The Multi-Linear material alone does not exhibit any hysteresis loop behavior and follows the backbone curve without energy dissipation. However, by combining the Elastic Perfectly Plastic (EPP) material with the Multi-Linear material, the resulting combined material exhibits residual displacement and hysteresis loop behavior

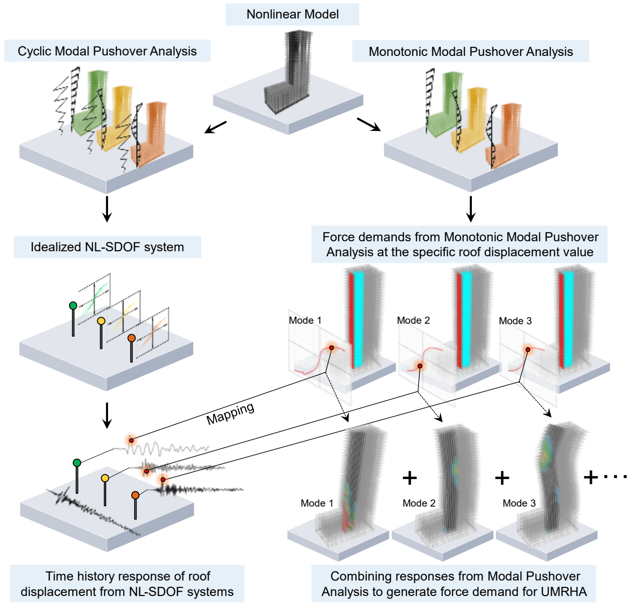

Figure 2. Overall process of the proposed technique for finding component-level force demand

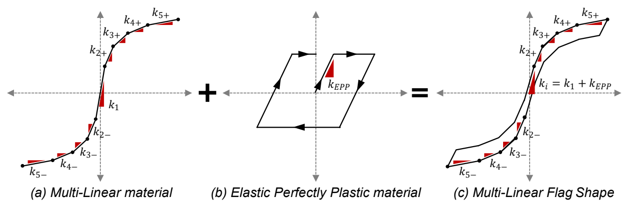

Figure 3. Backbone curve of Multi-Linear material, Elastic Perfectly Plastic material, and the combined Multi-Linear Flag Shape model

3. Case study buildings

The two case study buildings used in this study were obtained from Najam & Warnitchai [3]. These buildings, denoted as B1 and B2, have 34 and 44 stories respectively, and they are existing structures located in Bangkok, Thailand. The chosen case study buildings were initially designed to withstand wind loads but lacked ductile detailing. This is because Bangkok has traditionally been perceived as an area with low seismic risk, leading to most existing buildings being designed to resist gravity and wind loads without giving sufficient consideration to seismic forces [6]. The structural system of these buildings consists of flat slab-frames with RC shear walls in the core. The selected case study buildings have irregular shapes, with podiums in the first few stories and towers continuing up to the roof, as shown in Figure 4. Both buildings have mat foundations supported by piles [7]. Detailed nonlinear models of both buildings were created using Perform 3D [8].

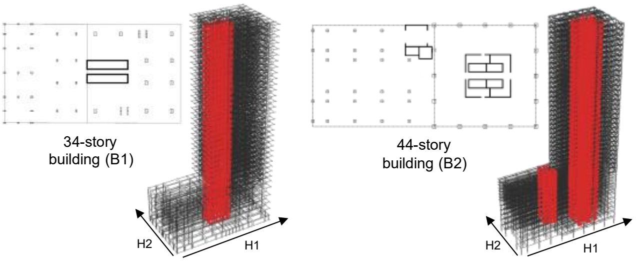

Figure 4. Nonlinear 3D model of case study buildings in Perform 3D

4. Ground motions

This study expects that the developed technique should be applicable to all types of ground motions. To demonstrate this, the selected ground motions should come from different categories to demonstrate various earthquake mechanisms. The aim was to assess the effectiveness of the proposed technique in capturing the nonlinear behavior of the structure under various seismic excitations. For this purpose, three horizontal ground motions with different response spectra will be chosen from the Pacific Earthquake Engineering Research Center (PEER) ground motion database. The first ground motion (named as EQ1) had a dominant pseudo acceleration at short periods, while the third ground motion (named as EQ3) was selected for its dominant pseudo acceleration at long periods. The second ground motion (named as EQ2) was chosen for its intermediate characteristics.

Additionally, EQ1 was chosen to have a significant impact on higher modes, while EQ3 was intended to primarily influence the first mode. This approach provided a comprehensive evaluation of the proposed technique to accurately capture the nonlinear response of the structure across multiple modes under different seismic excitations.

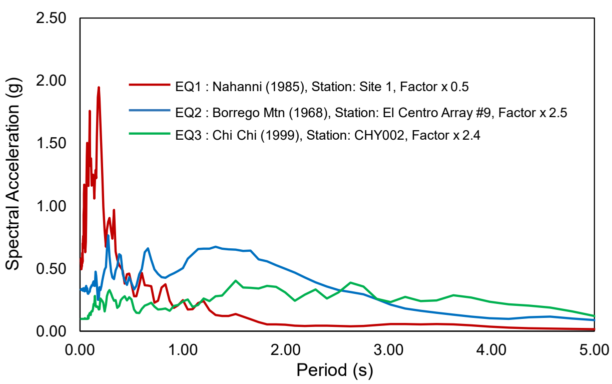

Figure 5. Response Spectra of selected ground motions (2.5% Damped)

3. RESULTS

The evaluation of the seismic response will be based on three cases that exhibit varying degrees of nonlinearity, ranging from low to high. The short period ground motion (EQ1) was scaled down by a factor of 0.5 to ensure the building's response remained within the low nonlinearity range. On the other hand, the long period ground motion (EQ3) was scaled up by a factor of 2.4 to increase the degree of nonlinearity of the response. The aim is to demonstrate that when the response exhibits a low degree of nonlinearity, both the UMRHA with the mapping technique and the previous UMRHA with a constant force ratio provide reasonably accurate results. However, for buildings with a high nonlinearity response, this study intends to show that only the proposed UMRHA technique is accurate.

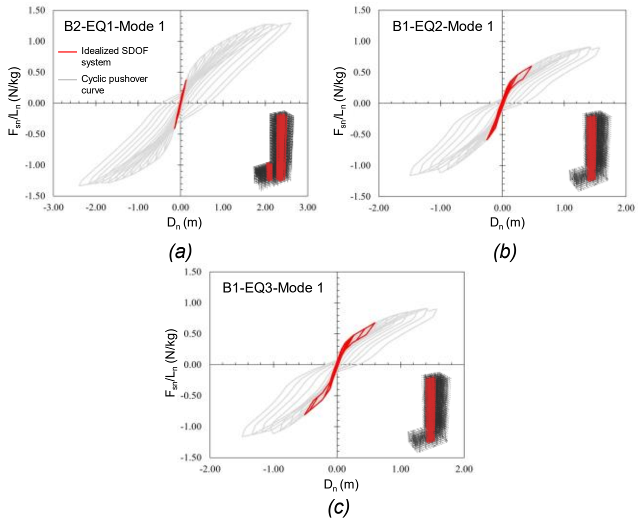

Figure 5. Response of the 1st-mode idealized nonlinear SDOF systems under ground motion

Figure 5 shows the response of the idealized nonlinear SDOF systems for the 1st-mode under different ground motion scenarios. From the results, it can be observed that response of the 44-story building (B2) under EQ1 experience low degree of nonlinearity (as shown in Figure 5a), while the response of the 34-story building (B1) under EQ2 and EQ3 exhibits a higher degree of nonlinearity (as shown in Figure 5b-c). For all cases, the response of the higher modes when subjected to the selected ground motion, exhibits a low degree of nonlinearity and is likely to remain elastic. This study considers up to five translational modes in each direction, as the elastic force demands from the higher modes are significant and cannot be neglected.

Figure 6 shows the comparison of the component-level force demands. In this case, the building exhibits a low degree of nonlinearity, as highlighted in Figure 5a. The results from this case indicate that both the UMRHA with the mapping technique and the previous UMRHA with the constant force ratio assumption can give reasonably accurate component-level force demands.

The 34-story building (B1) experiences a significant level of nonlinearity when subjected to EQ2 and EQ3, as shown in Figure 7 and 8. The results show that the previous UMRHA technique, which uses the constant force distribution assumption, produces a poor prediction at the component level. It is evident that the previous UMRHA technique underestimates the force demand of columns located in the lower stories. In contrast, the force demand estimation from the proposed UMRHA technique is more accurate and aligns closely with the actual demand from NLRHA, this highlights an improvement in the estimation of seismic demand.

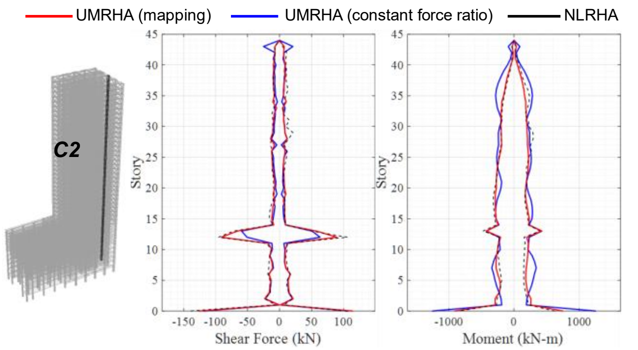

Figure 6. The comparison of component-level demands (B2 subjected to EQ1)

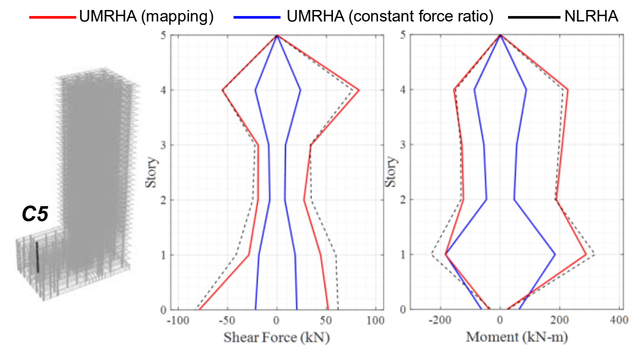

Figure 7. The comparison of component-level demands (B1 subjected to EQ2)

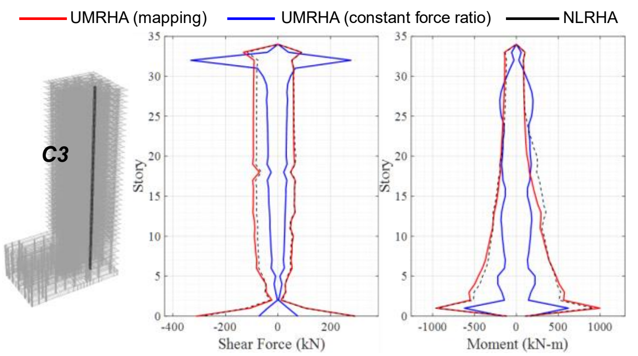

Figure 8. The comparison of component-level demands (B1 subjected to EQ3)

4. CONCLUSIONS

This study has shown that the proposed Multi-Linear Flag Shape (MLFS) hysteretic model can accurately capture the unsymmetric hysteretic behavior for both the positive and negative sides of a building. Therefore, when an appropriate hysteretic model is applied, the component-level force demand can be accurately estimated by UMRHA using both the constant force ratio and response mapping techniques. However, when the degree of nonlinearity is high, UMRHA using the constant force ratio technique provides poor predictions for component-level demand. On the other hand, UMRHA using mapping techniques can accurately estimate force demand at every degree of nonlinearity.

5. REFERENCE

[1] T. Mehmood, P. Warnitchai, and P. Suwansaya, “Seismic Evaluation of Tall Buildings Using a Simplified but Accurate Analysis Procedure,” *Journal of Earthquake Engineering*, vol. 22, no. 3, pp. 356–381, 2018, doi: 10.1080/13632469.2016.1224742.

[2] Chopra A.K and Goel R.K, “A modal pushover analysis procedure for estimating seismic demands for buildings,” *Earthq Eng Struct Dyn*, vol. 31, no. 3, pp. 561–582, 2002.

[3] Najam F.A. and P. Warnitchai, “A modified response spectrum analysis procedure to determine nonlinear seismic demands of high-rise buildings with shear walls,” *The Structural Design of Tall and Special Buildings*, vol. 27, no. 1, p. e1409, 2018.

[4] A. Pradhananga, “Evaluation of Nonlinear Seismic Response of mid-rise Buildings with RC Walls and Infill Walls by using a Modified Response Spectrum Analysis (MRSA) Method,” Master thesis, Asian Institute of Technology, Bangkok, 2020.

[5] W. Y. Kam, S. Pampanin, A. Palermo, and A. J. Carr, “Self-centering structural systems with combination of hysteretic and viscous energy dissipations,” *Earthq Eng Struct Dyn*, vol. 39, no. 10, pp. 1083–1108, 2010.

[6] M. Suthasit, “Nonlinear Modeling of Gravity Load Designed Reinforced Concrete Buildings for Seismic Performance Evaluation (Master thesis No ST-07-06),” *Asian Institute of Technology, Bangkok*, 2007.

[7] F. Najam and P. Warnitchai, “A modified response spectrum analysis procedure to determine nonlinear seismic demands of high-rise buildings with shear walls,” *The Structural Design of Tall and Special Buildings*, vol. 27, no. 1, p. e1409, 2018.

[8] Computer and Structure Inc (CSI), “Nonlinear Analysis and Performance Assessment for 3D Structures user Guide.” Computers and Structures, Inc, Berkeley, CA, 2018.

6. AUTHOR BIOGRAPHIES

Jirapat Watchawong holds a M.Eng in Civil (Structural) Engineering from Asian Institute of Technology (AIT), Thailand, in 2023. He is currently a member of the seismic losses and impacts research team, where he is involved in the development of a catastrophe model for Chiang Mai and Chiang Rai, Thailand. Jirapat's primary research interests include the evaluation of nonlinear seismic response using modal decomposition techniques, sensitivity analysis, and seismic fragility analysis of reinforced concrete buildings.

Pennung Warnitchai has D.Eng. in Civil Engineering from University of Tokyo, Japan and is currently the Professor in Structural Engineering Field of Study, School of Engineering and Technology, Asian Institute of Technology (AIT), Thailand. Prof. Warnitchai is also actively involved with the Disaster Preparedness, Mitigation, and Management Field of Study at AIT. Besides, Prof. Warnitchai association with AIT, he has been part of various significant elective and appointed offices both in Thailand as well as in the region. Some of Prof. Warnitchai current professional affiliations include: Scientific Board Member, The Global Earthquake Model; Member, National Earthquake Committee of Thailand; Chair, Chapter on the Effects of Earthquakes and Wind Loads, Engineering Institute of Thailand under H.M. the King’s Patronage; Member, Civil Engineering Chapter, Engineering Institute of Thailand under H.M. the King’s Patronage.

DISCLAIMER

This extended abstract presents findings from the same study conducted by the author. Please be aware that the complete research paper, which offers a comprehensive analysis, will be published at another international conference (WCEE2023) and will not be available through this conference. Therefore, the author kindly requests that you consider referencing the upcoming full research paper, which will provide more detailed insights into the study.

Jirapat Watchawong, October 2023