Energy-based seismic performance assessment of asymmetric building frame

P. Halder1[a], S. Bhattacharjya2[b] and S. Chakraborty3[c]

[a,b,c] Department of Civil Engineering, Indian Institute of Engineering Science and Technology, Shibpur, Howrah 711103, India,

1. INTRODUCTION & OBJECTIVE

Seismic performance assessment is a process that evaluates a structure's capacity to withstand earthquakes by analyzing its behavior under seismic loads to determine its resistance to damage or collapse. By utilizing nonlinear time history analysis (NLTHA), the performance can be assessed more accurately. However, NLTHA-based assessment is time-consuming. Therefore, nonlinear static analysis base simplified methods, e.g., non-linear static pushover analysis (NSP), modal pushover analysis (MPA), energy-based pushover analysis (EB-MPA), etc., are used for performance assessment. Among those, the MPA is the most widely used static method to estimate the seismic performance of structures. From the existing literature, it is observed that the MPA provides valuable insights into the seismic performance of a structure[1]. In this regard, the EB-MPA method, which is based on the energy balance concept, is also gaining significant attention. In this approach, the absorbed energy within the structure is considered as the resisting force along the capacity curve. The target displacement is then identified at the intersection of the capacity and demand curves, both of which are expressed in the energy domain. This method introduces innovative applications of strain energy, providing a more accurate representation of a structure's behavior under seismic loads. Hernandez-Montes et al.[2] initially introduced the EB-MPA to address the distortions observed in pushover curves, particularly those associated with higher modes. This approach is subsequently extended to asymmetric-plan buildings by some researchers[3-5]. However, still there are limited research that addresses the influence of torsional modes in asymmetric buildings. Keeping this in view, an attempt is made in the present study to evaluate the effectiveness of the EB-MPA in assessing the seismic performance of a structure considering a three-dimensional (3D) model incorporating torsional modes. In order to do so, in a 3D symmetric steel building, 15% mass eccentricity is introduced, both in x- and y-directions, to make it asymmetric and modeled in SAP2000 finite element analysis software for MPA and NLTHA. The peak response of the structure is obtained using NLTHA with far-field ground motions selected from the FEMA-P695[6]. Subsequently, the MPA and EB-MPA methods are utilized to predict the peak response of the same buildings considering dominated response component in torsional modes along with the other modes. The resulting responses are then compared with NLTHA to study the effectiveness of the EB-MPA compared to MPA.

2. RESULTS & HIGHLIGHTS OF IMPORTANT POINTS

In order to demonstrate the advantage of the EB-MPA over conventional MPA, a 3D symmetric steel building is adopted from Landolfo et al.[7] and modeled in SAP2000 software. To evaluate the influence of higher modes, nine vibration modes are considered for both symmetric and asymmetric cases. The pushover curves of symmetric and asymmetric buildings are shown in Fig. 1(a) and Fig. 1(b), respectively, for various modes. It may be noted that in case of a symmetric building, the capacity curves corresponding to the purely torsional modes are not well-defined, whereas the capacity curves for torsional modes are present in case of the asymmetric building, which has been considered along with other modes to perform the static analysis.

E-mail: [a]pujaiiestsce@gmail.com , [b]soumya@civil.iiests.ac.in, [c]schak@civil.iiests.ac.in

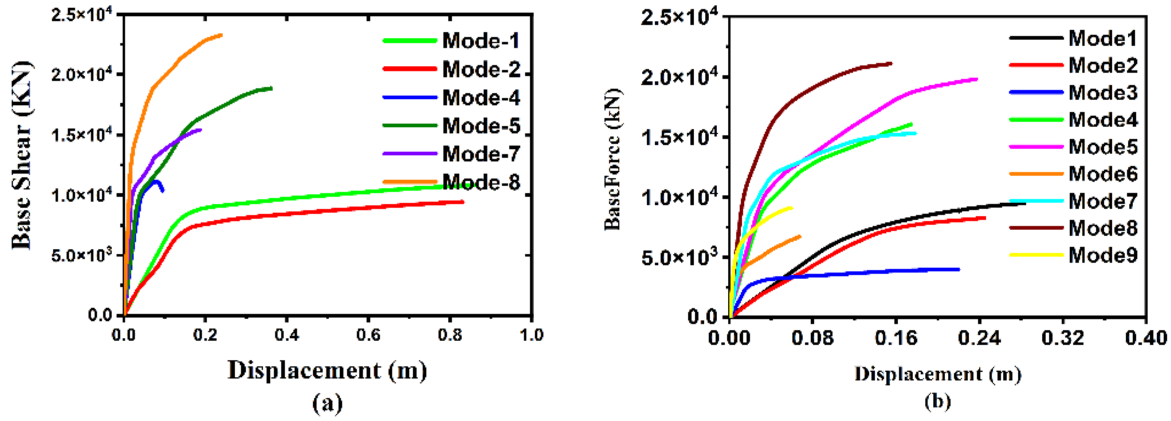

Fig. 1 Capacity curves of (a) symmetric frame (b) asymmetric building

A comparative study is performed to estimate responses by the EB-MPA and usual MPA, comparing those with the response obtained by NLTHA using the horizontal (X-and Y-component) pairs of ground motion data selected from the FEMA-P695[6]. The error percentages are shown in Fig.2 and Fig.3 for symmetric and asymmetric buildings, respectively. It can be noted that the EB-MPA method performed well for symmetric and asymmetric structures for most of the ground motions. The peak displacements are closer to the responses of the NLTHA method in the case of EB-MPA than MPA. The reason is that EB-MPA explicitly accounts for the energy dissipation in a structure during seismic events. Also, the interaction between different vibrational modes can be significant, especially in the inelastic range. EB-MPA may better capture these interactions due to its energy-based formulation, which implicitly considers the overall energy exchange and distribution among different modes. By capturing these aspects more accurately, the method can better approximate the true nonlinear behavior of the structure, leading to peak responses closer to those obtained from NLTHA. Also, EB-MPA can incorporate the effects of higher modes more effectively, improving the accuracy of the response prediction. Therefore, the error percentages are also less in the case of EB-MPA than MPA for both structures.

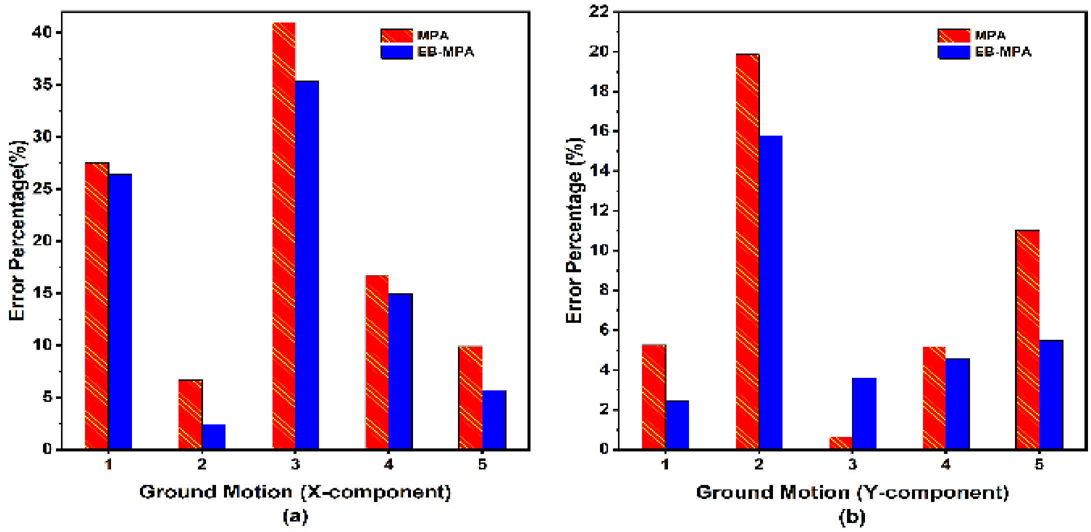

Fig.2 Comparison of percentage error for symmetric structure (a) X-component (b) Y-component of ground motion

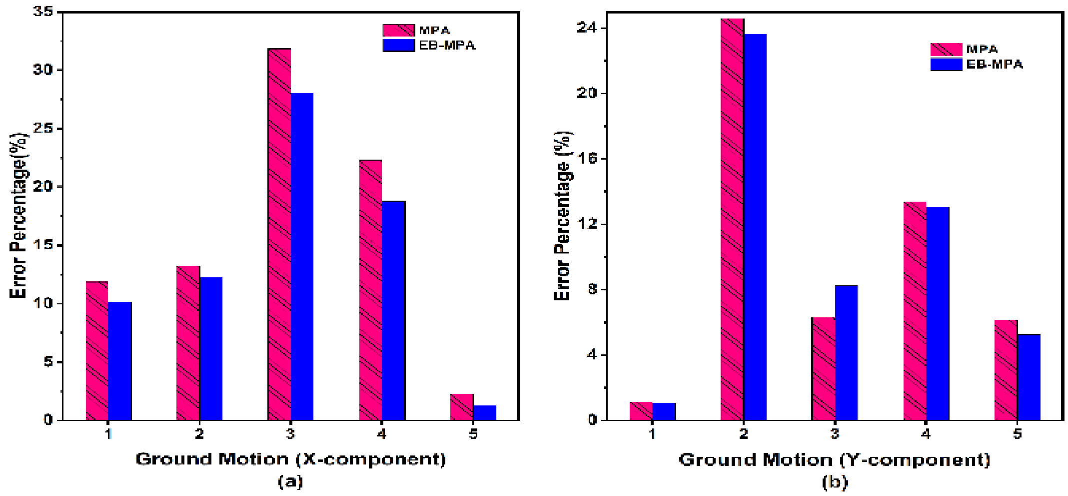

Fig.3 Comparison of percentage error for asymmetric structure (a) X-component (b) Y-component of ground motion

The lower percentage of error observed for the x-component of ground motion in EB-MPA compared to MPA is likely due to a combination of the structure's geometry, dominant mode shapes, energy dissipation characteristics, and the specific characteristics of the ground motion in the x-direction. Asymmetric structures exhibit greater vulnerability in peak responses compared to symmetric structures, largely due to the significant impact of torsional modes on structural performance. This irregularity notably affects the inelastic deformation capacity of the structure. The EB-MPA method is noted to be effective in analyzing the nonlinear behavior of asymmetric structure and performs better than the MPA method for mass-eccentric structure.

REFERENCES

1. A. K. Chopra, and R. K. Goel, “A modal pushover analysis procedure for estimating seismic demands for buildings,” *Earthq Eng Struct Dyn*. **31**, pp. 561–582, 2002.

2. E. Hernández-Montes, O. S. Kwon, and M. A. Aschheim, “An energy-based formulation for first- and multiple-mode nonlinear static (Pushover) analyses,” *Journal of Earthquake Engineering*. **8**, pp. 69–88, 2004.

3. S. Soleimani, A. Aziminejad, and A. S. Moghadam, “Approximate two-component incremental dynamic analysis using a bidirectional energy-based pushover procedure,” *Eng Struct*. **157**, pp. 86–95, 2018.

4. R. Zare Bidoki, and M. Shayanfar, “An energy-based pushover-analysis with torque-effects in assessment of the structures with asymmetric plan,” *Soil Dynamics and Earthquake Engineering*. **108**, pp. 58–68, 2018.

5. S. Soleimani, A. Aziminejad, and A. S. Moghadam, “Extending the concept of energy-based pushover analysis to assess seismic demands of asymmetric-plan buildings,” *Soil Dynamics and Earthquake Engineering*. **93**, pp. 29–41, 2017.

6. Agency FEM. Quantification of Building Seismic Performance Factors. FEMA P695, Washington, DC; 2009.

7. R. Landolfo, F. M. Mazzolani, Dan. Dubina, L. S. da. Silva, and Mario D’Aniello, *Design of Steel Structures for Buildings in Seismic Areas: Eurocode 8: Design of Steel Structures in Seismic Areas. Part 1-1, General Rules and Rules for Buildings*. ECCS, 2017.