On the assessment of MIDA method for mid-rise steel structures with non-symmetrical plan

M. Zanjanchi¹ and M. Mofid²,

Civil Engineering Department, Sharif University of Technology, Tehran, Iran

Abstract

Determination of nonlinear dynamic behavior of structures has always been one of the main goals for both structural and earthquake engineers. One of the newest methods for analyzing seismic behavior of structures is Modal Incremental Dynamic Analysis (MIDA). In fact, this method is an alternative to the Incremental Dynamic Analysis (IDA) which is a difficult and time-consuming method. Despite the MIDA's approximate results, advantages such as adequate accuracy, high speed, and low cost has made this method an efficient and appropriate approach. In all previous studies, the proposed models have had a regularized plan, hence, all the analyses have been carried out on a frame. In this study, the MIDA analysis is developed in an unsymmetric-plan type building by considering three structures with 4, 7, and 10 stories having irregularity in plan and thereafter, the accuracy of work has been examined. In this study, by a simplification, instead of considering an unconventional plan, we used a rectangular plan with an eccentricity of 15% between the center of mass and the center of rigidity. Comparing the results of this study with the IDA method proves the high level of accuracy of this method in assessing seismic demands.

KEY WORDS: Modal Incremental Dynamic; Incremental Dynamic Analysis; Unsymmetric-plan building; unconventional plan, Seismic demands

1. Introduction

Accurate estimation of seismic demand and capacity of structures is the main basis of Performance-Based Earthquake Engineering (PBEE). However, several methods are being proposed for investigation. Explicit attention to the inelastic behavior of structures is required for estimating the seismic demands at low performance levels such as life safety and collapse prevention. Nonlinear static processes are utilized as a part of the conventional performance evaluation of structural engineering, although Non-Linear Response Time History Analysis (NL-RHA) is one of the most precise methods for seismic demand computations. Many researchers have attempted over the last few years to complete the pushover analysis and to overcome the disadvantages of previous methods. Freeman et al. (1988) tried to apply the effects of the higher modes of structure on its failure mechanism. By providing the MMP method, they were able to detect the failure mechanism under higher modes, in addition to using the advantages of the pushover method [1]. In 2002, PRC method was presented by Sarvghad Moghadam. In this method, the effect of higher modes is considered; first, the structure is covered under different load distributions that are based on different shape modes [2]. In 2002, Chopra and Goel presented a method for calculating the seismic responses of structures. This method has been used from the concepts of non-linear static analysis (MMP) and spectral response analysis, in which the effect of higher modes is also considered [3]. Moreover, methods such as Incremental Modal Pushover Analysis (IMPA),
Modified Modal Pushover Analysis (MMPA), and Evaluation of energy-eased modal pushover analysis are also presented by researchers to improve the pushover method. [4, 5, 6] All the studies have mentioned here are restricted to two-dimensional frames and three-dimensional symmetric-plan structures. In recent years, researchers have attempted to generalize pushover analysis methods to unsymmetric-plan 3D type building structures to consider torsional effects. The following studies are of the most important studies that have been performed on this subject: Chopra et al. were able to develop the MPA method first in a regular 3D structure and then in a structure with irregularity in plan [7, 8, 9]. Pournsh et al. developed consecutive modal pushover procedure first in a structure having irregularity in one direction and then, considering irregularity in both directions [10, 11, 12]. Many researches have been conducted to investigate and estimate the behavior of asymmetric-plan building (e.g., [13-16]).

The studies performed on the development of pushover methods were presented up to this section, however, since the MIDA method is a combination of MPA and IDA methods, it is also essentially to express the history of IDA method. Nonlinear Incremental Dynamic Analysis (IDA) seems to be the most accurate structural analysis method under earthquake stimulation. This method has been first presented by Bertro in 1977 [17]. After them, many researchers have attempted to develop and complete the approach that can refer to Bruni et al., Zhou and Jalili Sadr Aabad [18, 19, 20]. High accuracy and providing the actual behavior of the structure are of the advantages of this method. In this method, the actual nonlinear behavior of the material as well as the actual dynamic nature of the earthquake stimulation is considered. The main method presented as an alternative to the IDA is the Modal Incremental Dynamic Analysis (MIDA) method, which some researchers call it MPA-Based IDA. This method was first presented by Mofid et al. in 2005 [21] and then it was utilized by Chopra and Henn in 2006 [22]. In 2011, this method was developed by Mofid et al. by means of trilinear idealization model [23].

In this study, it has been attempted to cover a broader range of structures where MIDA as a quick and accurate method can be applied in them by developing the method for steel structures with medium-and relatively short-height buildings that are irregular in the plan.

2. The Equation of Motion

As we know, solving the differential equation for a Single-Degree of Freedom (SDOF) structure is simpler and faster than solving the same equation for Multi-Degree of Freedom (MODF) structures. This issue is most important for doing nonlinear analyses. Thus, the idea of using a SDOF structure with the characteristics of a MODF structure was created. Now, the only important issue is to obtain the characteristics of the SDOF structure, including period, damping, yielding load, and stiffness. Additionally, the conversion factor of the responses obtained from the SDOF structure to the MODF structure must be determined.

Since in this study, the structures are modeled in 3D form, in order to obtain the characteristics of the SDOF structure, the equations of motion are first expressed and then the MIDA method is interpreted.

In the case of considering x and y components of earth motion, the equation of motion governing the structure response will be as follows:

\[ M\ddot{u} + f_s(u, \text{sign}\dot{u}) = -M\ddot{x}_x - M\ddot{y}_y \]  

where, it can also be written in matrix form as follows:
where, \( m \) is a diagonal matrix that is equal to the lumped mass of each story floor and \( I_o \) is a mass moment of inertia of each story. \( u_x \) and \( u_y \) are the horizontal displacements in \( x \) and \( y \) directions and \( \psi \) is related to the structure floor torsional motion. The hysteretic and nonlinear forces, \( f_s \), include \( f_{sx}, f_{sy} \) and \( f_{s\psi} \) representing the horizontal components of force in \( x \) and \( y \) directions and torsional force, respectively.

In the governing equation, the effect vector associated with the motion of the earth along \( x \) and \( y \) directions is as follows:

\[
\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} , \quad \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}
\]

The second side of the governing equation can be rewritten as the effective earthquake force, \( s\dot{u}_g \), along \( x \) and \( y \) directions, where \( S \) is the spatial distribution of the effective earthquake force:

\[
P_{\text{eff}}(t) = -s\dot{u}_g(t) = \begin{bmatrix} m_1 \\ 0 \\ 0 \end{bmatrix} \dot{u}_g(t) \quad \text{and} \quad -\begin{bmatrix} 0 \\ m_1 \end{bmatrix} \dot{u}_g(t)
\]

\[
s = \sum_{n=1}^{3N} \sum_{s=1}^{\Gamma_n} M_n \phi_n = \sum_{n=1}^{3N} \sum_{s=1}^{\Gamma_n} \begin{bmatrix} m\phi_{nx} \\ m\phi_{ny} \\ I\phi_{n\theta} \end{bmatrix}
\]

where, \( \phi_{nx}, \phi_{ny}, \) and \( \phi_{n\theta} \) indicate the modal shapes of the structure vibration in two transitional and torsional directions and also:

\[
\begin{align*}
\Gamma_n &= \frac{L_n}{M_n}, \quad M_n = \phi^T_n M \phi_n, \quad L_n = \begin{bmatrix} \phi^T_n m_1 \\ \phi^T_n m_1 \end{bmatrix}
\end{align*}
\]
3. MIDA Method

Incremental Dynamic Analysis (IDA) are capable of well illustrating the demand of structures at different levels of the earthquake. Assessing seismic demands under different levels of earthquakes by using an approximate and sufficient accuracy approach will save time. Changes can be made in the calculation speed when the analysis of a MDOF structure is not carried out as nonlinear dynamic. In the MIDA method, non-linear dynamic analysis of the MDF structure has not been used to obtain IDA curves. To achieve this goal, the entire structure is equivalent to a single degree of freedom structure and then evaluated with a modal pushover analysis method. It can be changed in the calculation speed when the analysis of a MDOF structure is not carried out as nonlinear dynamic.

The MIDA procedure to estimate the seismic demands for an unsymmetric-plan multistory building is presented as a sequence of steps found below:

Step 1- Design and Modeling of Structures: First, the structures are linearly analyzed and carefully designed and the dynamic properties of the structures including periods and mode shapes are obtained in all three components x, y and θ.

Step 2- Pushover Analysis and Obtaining Structures Capacity Curve: In order to model a MDOF structure with SDOF structure, the structure capacity curve relative to its seismic properties is required. The pushover analysis for the lateral load, $S_n^*$ [Equation 10], is performed on structures in each mode and the base shear-roof displacement curve, which is the same frame capacity curve, is obtained.

$$
S_n^* = \begin{bmatrix}
  m\phi_{nx} \\
  m\phi_{ny} \\
  L_o\phi_{b0}
\end{bmatrix}
$$

(10)

Step 3- Idealize the Pushover Curve as a Bilinear Curve: In order to perform a SDOF structural analysis, the force-displacement model is required. Considering the software limitations and also keeping the wok simplicity in this method, the force-displacement model should be bilinear. Therefore, the MDOF structure capacity curve in the dominant direction should be approximated by a bilinear model in order to obtain the characteristics of a SDOF structure from it.

Step 4- Obtaining the SDOF System Characteristics: To convert the main MDOF structure to an equivalent SDOF structure, it is applied in such a way that the SDOF structure has a period and damping equal to the period and damping of the main MDOF structure and additionally, its load-deformation curve is obtained from the MDOF structure as shown in figure (1).
Consequently, the following relationships can be written:

\[
\frac{F_{ny}}{L_n} = \frac{V_{ny}}{M_n^*} \quad \text{(12)}
\]

\[
D_{ny} = \frac{u_{ny}}{\Gamma_{ny} \phi_m} \quad \text{(13)}
\]

Where:
- \( F_{sn} \) = the scaled stiffness of the system, proportional to time response of the structure
- \( V_{bn} \) = yielding strength
- \( U_{rn} \) = yielding displacement of the roof of the \( i \)th mode of vibration,
- \( \alpha \) = the strain hardening angle of the material,
- \( \phi_m \) = the \( \phi \) at the roof in the direction of the selected pushover curve

\( M_n^* \) and \( \Gamma_n \) correspond to the direction of ground motion under consideration (x or y) and equal:

\[
M_n^* = \Gamma_n L_n \quad \text{(14)}
\]

Step 5 - Analyzing SDOF Structure: At this step, the obtained SDOF structure is subjected to the intended earthquake record and the nonlinear time-history analysis is performed in order to calculate a maximum displacement (\( D_n \)). The SDOF structure acts as a nonlinear spring, which the force-displacement characteristic of this spring is obtained in step 4.

Step 6 - Calculating the Maximum Displacement of MDOF Structure: By multiplying the coefficients \( \Gamma_{ny} \) and \( \phi_{yn} \) from the displacement obtained in the previous step, the maximum displacement of the MDOF structure will be calculated:

\[
u_{xn} = \Gamma_{nx} \phi_{xn} D_n \quad \nu_{yn} = \Gamma_{ny} \phi_{yn} D_n \quad \text{(11)}
\]

Step 7 - Performing Pushover Analysis and Extracting the Results: The main MDF structure will be pushed, according to \( S_{n}^* \) lateral loading pattern, to the target displacement \( u_{rn} \) which was obtained in the previous step. Then, the maximum drift of each stories will be computed for the considering level of the scaled earthquake record.

Step 8 - Combination of Modes’ Effect: At the end, the results obtained from different modes must be combined. For this purpose, the maximum roof displacement, the relative story displacement, and the maximum plastic rotation obtained in each mode at the identical seismic level are combined using SRSS rule.
### 2 Modeling and Record Selection

The studied structures are 4, 7, and 10-story buildings, which their structural system is moment-resisting frame. In addition, the height of each story is 3m and the building has 5 spans of 4m in the x direction and 3 spans of the same length in the y direction. The 3D view of the 4-story building is shown in Figure 2.

The structures were primarily designed by assuming linear behavior for the materials, influencing P-Δ effect, perfectly rigid beam and column connections, and not considering the dimensions of the panel. The followings were also considered in the design:

- The buildings are placed on soil type II.
- The building gravity loading is in accordance with the American standard for loading (ASCE7-10) [24].
- The building lateral loading is according to the American standard for loading (ASCE7-10).
- Designing of the steel members is performed based on American standard for steel structures (AISC360-10) [25].

To create an asymmetry, the story masses are distributed in an unbalanced way in such a way, each story has an eccentricity of 15% between the centers of gravity and rigidity along the y axis (figure 3).

All nonlinear analyses were performed by Open Sees software (Computers and Structures, 2004). Scaling acceleration records is one of the most important challenges for nonlinear time history analyses. Different Codes have proposed different approaches for scaling the acceleration records. In this study, the acceleration records are scaled up according to the fourth edition of the Iranian standard no. 2800 (code of practice for earthquake resistant design of buildings) [26], and also using the considerations suggested by Charney [27]. These three unsymmetric-plan buildings will experience coupled x-horizontal and torsional motions due to of the x-component of earthquake, which is the focus of this paper. In this regard, three ground motion records were used for the time history analysis, including Imperial Valley (1940), Northridge (1994) and Park field (1966).

### 3 Numerical Results

In this section, after verifying the modeling, the mode shape of each structure was drawn. For this purpose, it is taken from the participation of the six first mods of each structure. Figure 4 illustrates the mode properties of each structure, which includes the natural period of each mode and the horizontal components of x-direction as well as the torsional component. By having the mode shape and its values, the equations that have been explained in detail in the previous section were initiated to get solved.

Thereafter, the structures are pushed according to force distribution $S_n^*$ to obtain the base shear curves based on the roof displacement, and then the curves are idealized with bilinear curves. Such pushover curves for the four
modes of the 10-story building where x component of displacements is dominant compared to their y component, are shown in Figure 5.

Figures 6, 7 and 8, compare the MIDA and the exact IDA for 3, 7, and 10-storey buildings for three ground motion records, respectively. Each figure is presented for maximum interstorey drift.

In order to estimate the seismic demands, the contribution of the first six ‘modes’ was included in the analysis of the unsymmetric building. As may be expected, the first mode by itself has an insignificant impact when it comes to estimating the story drifts, especially in the upper step of the earthquake (Figure 9). Also considering the response contributions of higher mode significantly enhancing the story drifts. As a way to not only check the precision of this method, merely for maximum displacement, story drifts at CM for Imperial Valley earthquake are displayed in figure 10.

4 Conclusion

- According to the single and multiple curves of IDA and MIDA, as well as considering the curves of IDA and MIDA difference percentage, it can be found that the MIDA method is capable of correctly assessing the structure behavior while the error of MIDA method not exceeding 15%.
- The error of MIDA method at lower levels of earthquake intensity is much lower, however, the difference between the two diagrams increases by increasing the earthquake intensity. The reason is due to the structure nonlinear behavior in higher earthquake intensities. In fact, in smaller scale factors, since the structure is in the linear region, the accuracy of the MIDA method is greater and is more consistent with the results of the IDA method. However, by increasing the earthquake intensity, the structure begins to exit from the linear region and moves towards nonlinear region. Moreover, this nonlinear behavior leads to make approximation in the work. Therefore, as the intensity of the earthquake increases and more structural elements enter the nonlinear region, the MIDA approach approximation is increased. But the MIDA method is still accurate enough in high-intensity earthquakes.
- The difference between the MIDA and IDA diagrams in the 4-story structure is very small; however, the greater the number of stories, the greater the difference can be found. This is caused by the effect of higher modes, especially the torsional modes, is increased with increasing the number of stories whereas the approximation of MIDA is also increased.
- In the analysis of 3D structures using the MIDA method, the first mode of the structure cannot solely give us a correct response of the structure; therefore, in such structures, the effect of higher modes should be considered, the base of which we used from the first six modes in the present study.
- The most important issue to note is that using a MDF systems for perform dynamic analysis (IDA method), is very time-consuming and increases with a steep slope with increase in the number of stories. This is while the structure analysis time in the MIDA method is much less than IDA. The computation
The time required for a 4-storey building is reduced from two days for an accurate result to only two hours for the approximate result.

5 Reference


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Figure 1. Properties of the nth- ‘mode’ inelastic SDF system from the pushover curve.

Figure 2. 3D view of the 4-story structure

Figure 3. Plan of selected unsymmetric-plan buildings.

Figure 4. Natural periods and modes of vibration of 4, 7 and 10 story unsymmetric-plan systems: (a) unsymmetric-plan of 4-story; (b) unsymmetric-plan of 7-story; and (c) unsymmetric-plan of 10-story.

Figure 5. Bilinear idealization of the pushover curve of 10 story building

Figure 6. Comparing the single IDA and MIDA curve for maximum interstorey drift for three records for 4 story building.

Figure 7. Comparing the single IDA and MIDA curve for maximum interstorey drift for three records for 7 story building.

Figure 8. Comparing the single IDA and MIDA curve for maximum interstorey drift for three records for 10 story building.

Figure 9. Influence of higher modes in the accuracy of MIDA method.

Figure 10. Story drifts at CM for the first five step of Imperial Valley earthquake.
Figure 1.

Figure 2.
Figure 3.
Figure 4.
Figure 5.

Figure 6.
Dr. Massood Mofid is a professor of Civil Engineering Department at Sharif University and completed his Ph.D. studies at Rice University.

email: mofid@sharif.edu, Tel.: +98 21 66014828; fax: +98 21 66014828

Moein Zanjanchi completed his undergraduate studies at Sharif University in 2016 and is now Ph.D. candidate at K.N. Toosi University. His research interests are in the area of Structural Dynamics and Earthquake Engineering, Seismic Design of Steel and Concrete Structures, Finite Element Analysis and Rehabilitation.

email: moeinzanjanchi@alum.sharif.edu, Tel.: +98 935 582 9613