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# Incremental dynamic analysis and vulnerability analysis of structures under bidirectional ground motion inputs

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## ABSTRACT

Commonly the seismic response analysis of structures is based on the result of unidirectional input, i.e., ground motions inputs are separately considered along the two main axes of structures for independent analysis. However, actual structures are three-dimensional in nature. Due to the functionality and architectural modeling requirements, there are often cases where the locations of mass center and stiffness center do not coincide. Ground motions also compose of multidimensional components. Research results also show that the bearing capacity of columns under bidirectional action is quite different than unidirectional action cases. The unidirectional input approach may be applicable to the elastic analysis of the regular symmetric structure, but for the irregular structures where the center of mass and the stiffness center do not coincide, this approach is unreasonable. Therefore, it is reasonable to consider bidirectional ground motion inputs for structure dynamic analysis. In this paper, bidirectional ground motions constructed by using random combination of unidirectional ground motions are selected as input, and two uniaxial eccentric 4- and 12-storey RC frame structures are designed. The incremental dynamic analysis and vulnerability of structures are compared. The analysis results provide a theoretical basis for the future structure seismic design.
***Key words*****:** earthquake; seismic design; bidirectional ground motion; incremental dynamic analysis; vulnerability analysis

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## 1. INTRODUCTION

The seismic response analysis of structures has always been based on displacement, shear force, etc. In recent years, some new concepts have been proposed, such as the seismic performance of structures mentioned in the performance-based seismic design concept. The performance-based seismic design method was proposed by American scholars in the 1990s. This method can determine the performance target according to the importance and functionality of buildings, and adopt different seismic fortification standards according to different performance targets, which can overcome the current limitation of the seismic design concept and makes it easy for the owner to understand what kind of actual building performance can be obtained after paying a certain amount of investment (Yi 2003). On this basis, some scholars combined the structural reliability method with the performance-based seismic design theory, proposed a structural seismic vulnerability analysis method by using incremental dynamic analysis (IDA). In this paper, the IDA and vulnerability analysis of structures under unidirectional and bidirectional ground motion inputs are performed respectively. By comparing IDA curves and vulnerability curves, the difference of the structure under the two types of ground motion inputs is obtained.

## 2. STRUCTURAL INCREMENTAL DYNAMIC ANALYSIS

### *2.1 Method and Principle*

The structure IDA refers to the amplitude modulation processing of the selected ground motions according to the selected earthquake intensity index (IM) to obtain ground motions with a small to large earthquake intensity index, and nonlinear time history analysis of structures to obtain structural damage indicators (DM) under the influence of the series of ground motions. Each ground motion intensity index and corresponding structural damage index are plotted as “IM-DM” curves, which are called IDA curves. Because of the large deviation of the analysis results under different ground motions, IDA under multiple ground motions is generally required for the structure, and multiple IDA curves are analyzed statistically.

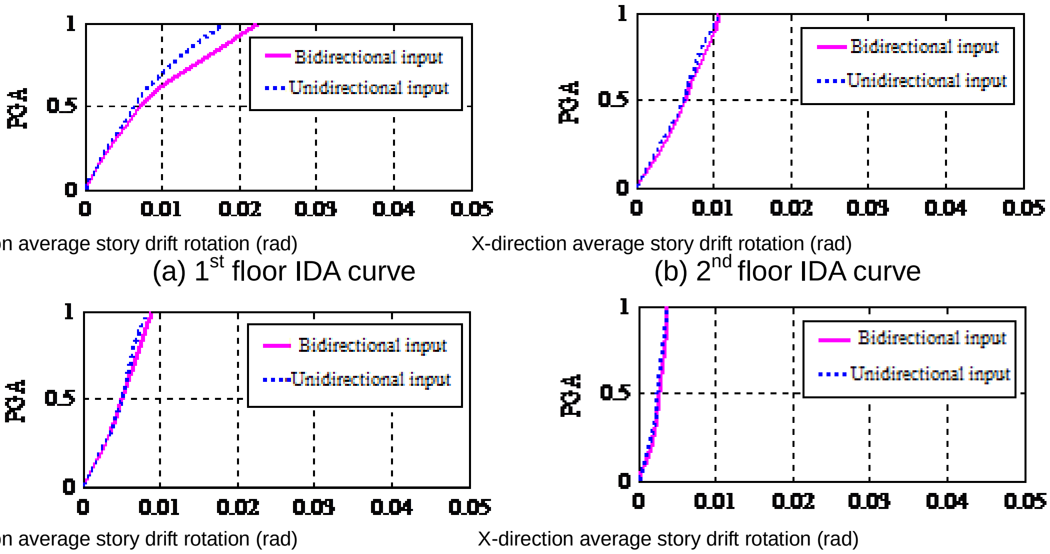
Obviously, to perform structural IDA, it is need to select the adopted earthquake intensity indicators and structural damage indicators first. At present, the strength indicators commonly used in IDA include peak ground acceleration (PGA) and spectral acceleration values corresponding to the fundamental period of the structure. This paper uses PGA as the ground motion intensity index. As for structural damage indicators, the commonly used indicators include vertex displacement, story drift rotation, base shear, and column foot curvature (Qiu 2001, He 2016, Shome 1999). The most commonly used one is the story drift rotation, which can be more comprehensive in the damage degree of structures. The maximum story drift rotation is used as a structure damage index in this paper.

### *2.2 Floor Distribution of IDA Curves*

In this paper, four reinforced concrete frame structures with one-way eccentricity in the X direction (longitude direction of the structure) are designed as examples, i.e., two four-story frame structures DC1.1 and DC1.5, and two 12-storey frame structures GC1.1 and GC1.5. Here the numbers 1.1, and 1.5 represent torsion irregularity coefficients. The structural fortification intensity is 8 degrees (0.2 g), the site category is

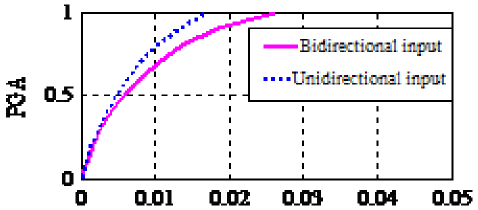
Class II, and the design earthquake grouping is group I. For ease of description, herein "DC1.5X" represent the multistory structure with a torsion irregularity coefficient of 1.5 and X direction is designated as the main input direction, and "GC1.1Y" indicates that the tall building structure with the torsion irregularity coefficient of 1.1 and Y direction is designated as the main input direction. When X is the main direction of seismic input, and the torsion irregularity coefficient is 1.5, the amplification effect of the bidirectional ground motion input is more obvious, therefore multistory and tall structures with the torsion irregularity coefficient of 1.5 are used as examples. Under unidirectional and bidirectional input, the IDA curve of each floor with the average story drift rotation as damage index is shown in Figs. 1 and 2.

For the multistory structure, the difference between results of unidirectional and bidirectional inputs shows that at the bottom of the structure (1st floor) the difference is most obvious, and when the PGA exceeds 0.4 g, the difference increases significantly. At the 2nd and 3rd floors of the structure, the difference is relatively small. It is also clear that story drift rotation under bidirectional ground motion inputs is slightly larger than that under unidirectional ground motion inputs. For the top floor of the structure, the difference of story drift rotation under two type of ground motion inputs is the smallest. For tall building structures, by comparing the results of two type of ground motion inputs it can be seen that the difference is significant in the first three floors at the bottom of the structure when the PGA of input is larger than 0.5g and the difference is positively proportional to the PGA of input. For the 4th floor and upper floors, the difference is negligibly small. For both multistory structure and tall building structure, the story drift rotation is relatively larger in the lower part of the structure than the upper part and the story drift rotation under bidirectional ground motion inputs is obviously larger than unidirectional inputs cases in the lower part of the structure. For the mult-story structure, the bottom floor is a weak layer, and for the tall building structure, the 2nd and 3rd floors are weak floors.

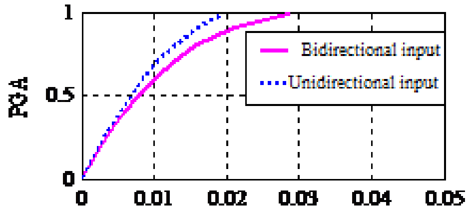



(a) 1st floor IDA curve
(b) 2nd floor IDA curve
(c) 3rd floor IDA curve
(d) 4th floor IDA curve

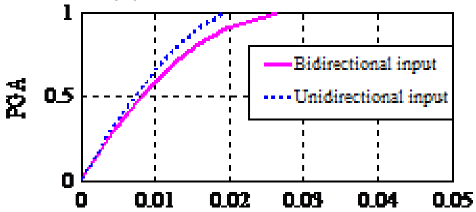
Fig. 1 The IDA curve for each floor of DC1.5X



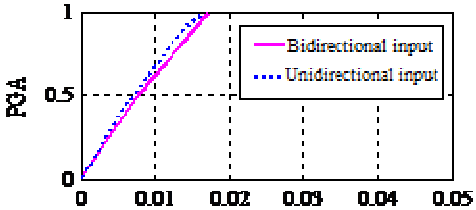

X-direction average story drift rotation (rad)
(a) 1st floor IDA curve



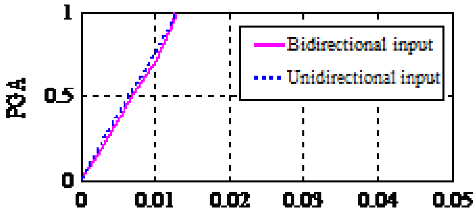

X-direction average story drift rotation (rad)
(b) 2nd floor IDA curve



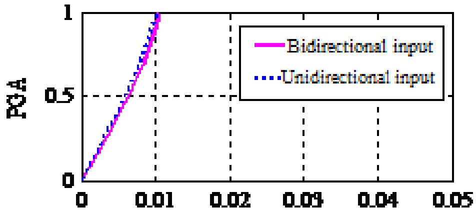

X-direction average story drift rotation (rad)
(c) 3rd floor IDA curve



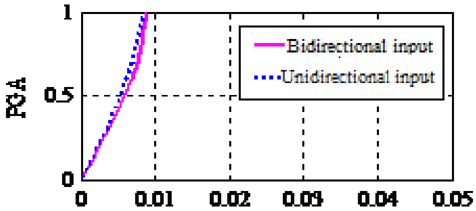

X-direction average story drift rotation (rad)
(d) 4th floor IDA curve



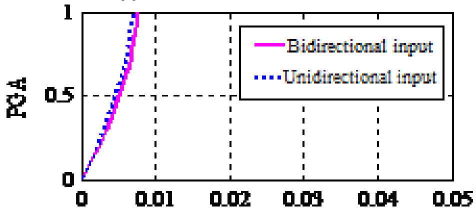

X-direction average story drift rotation (rad)
(e) 5th floor IDA curve



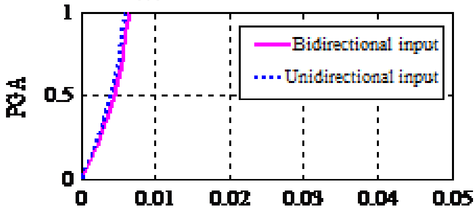

X-direction average story drift rotation (rad)
(f) 6th floor IDA curve



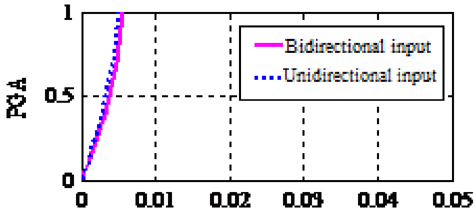

X-direction average story drift rotation (rad)
(g) 7th floor IDA curve



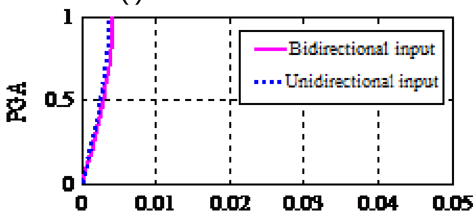

X-direction average story drift rotation (rad)
(h) 8th floor IDA curve



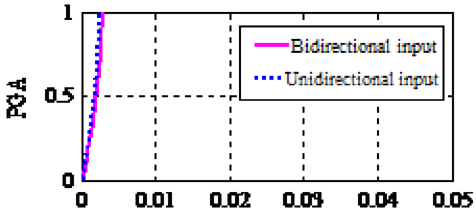

X-direction average story drift rotation (rad)
(i) 9th floor IDA curve




X-direction average story drift rotation (rad)
(j) 10th floor IDA curve




X-direction average story drift rotation (rad)
(k) 11th floor IDA curve




X-direction average story drift rotation (rad)
(l) 12th floor IDA curve

Fig. 2 The IDA curves for each floor of GC1.5X

## 3. STRUCTURAL VULNERABILITY ANALYSIS

*3.1 Structural Vulnerability Analysis*

If EDP stands for the engineering demand parameter of the structure (in this paper, the maximum story drift rotation) and the given earthquake intensity index is im (in this paper, PGA) then under this condition the probability that EDP is greater than a certain limit state LS is $P(EDP > LS|IM = im)$. It can be seen that the key step to solving structural vulnerability lies in determining the statistical distribution type of EDP. According to Shome (1999) and Miranda (2003), EDP is considered to obey the lognormal distribution. Thus, the structural vulnerability formula is

$$P(EDP > LS|IM = im) = 1 - P(EDP < edp|IM = im) = 1 - f\left[\frac{\ln edp - \mu_{\ln EDP|IM=im}}{\sigma_{\ln EDP|IM=im}}\right] \quad (1)$$

where edp is the limit value of the demand parameter corresponding to the limit state LS.

*3.2 The Limit State of Structure*

According to IDA-based seismic vulnerability analysis, it is necessary to determine the limit state of the structure. The general practice here is to divide several performance levels according to different damage states of the structure under different intensity earthquakes, and then give corresponding quantitative indicators according to the characteristics of each performance level.

In Huang (2012), the author conducted elastoplastic time history analysis of multistory RC frame structures with different heights, and statistically analyzed the story drift rotation limit for each performance level. Based on above work and combined with the requirements of the current code specification, the performance level (limit state) and its corresponding story drift rotation limit are shown in Table 1.

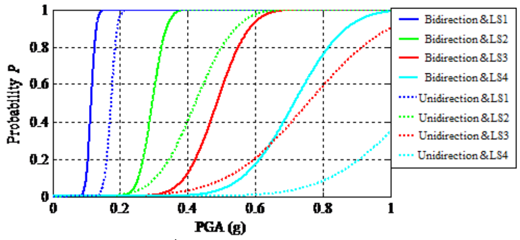
Table 1 The limit state and corresponding story drift

| Performance level | Story drift rotation limit |
|---|---|
| intact (LS1) | 1/550 |
| Minor damage (LS2) | 1/200 |
| Moderate damage (LS3) | 1/100 |
| Severe damage (LS4) | 1/50 |

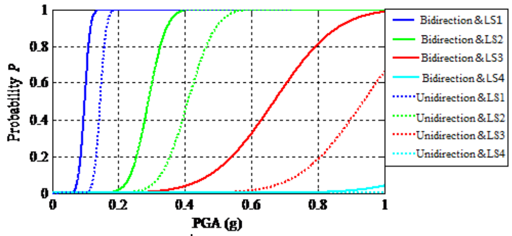
*3.3 Distribution of Vulnerability along the Floor Height*

The fragility curve of each floor under unidirectional and bidirectional ground motion inputs for multistory is shown in Fig. 3.

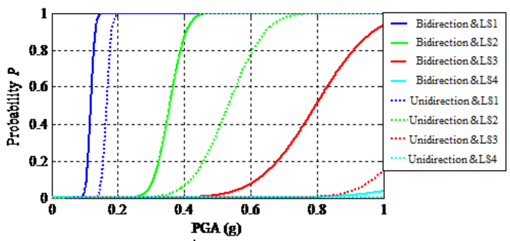
For all the 4 limit states LS1to LS4, the corresponding probability under bidirectional ground motion inputs is larger than that under unidirectional ground motion inputs, and along the height of structure (from the bottom to the top), the probability to each limit state decreases. In the 1$^{st}$ floor of the structure, the damage corresponding to all the 4 limit states occurs, in the 2$^{nd}$ and 3$^{rd}$ floors the damage corresponding to limit states LS1 to LS3 occurs, while in the 4$^{th}$ floor only the damage corresponding to limit states LS1 and LS2 occurs. It is clear that the 1$^{st}$ floor is the weak floor of the structure and the structural vulnerability under bidirectional inputs is obviously high than that under unidirectional inputs.



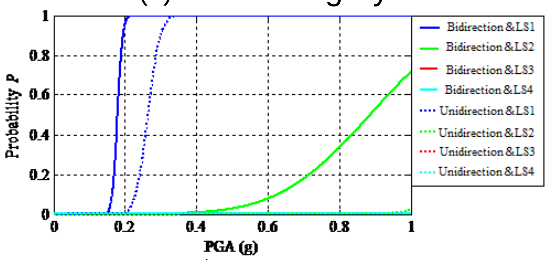

(a) 1st floor fragility curve




(b) 2nd floor fragility curve




(c) 3rd floor fragility curve




(d) 4th floor fragility curve

Fig. 3 Fragility curve for each floor of DC1.5X

The 3-dimensional surface of structural fragility for each floor is presented in Fig. 4. It can be seen that for the limit state LS1 the structural fragility changes gradually along the floor height. For limit states LS2 to LS4 there exist peaks in the fragility surfaces which indicates that the maximum structural fragility locations occur in the 2nd or 3rd floor of the structure, i.e., 2nd and 3rd floors are the weak floors of the structure. For some floors of the structure, not all the damage corresponding to 4 limit states occurs, e.g., for the floors above the 10th floor the damage corresponding to limit state LS3 does not occur and for the floors above 8th floor the damage corresponding to limit state LS4 does not occur.

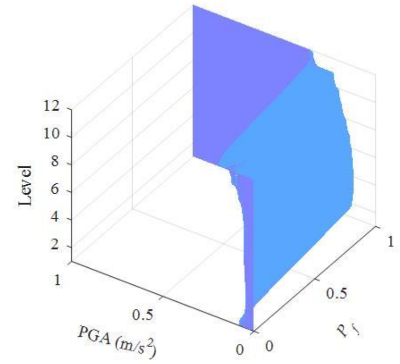
## 4. Conclusions

The main conclusions obtained are as follows.

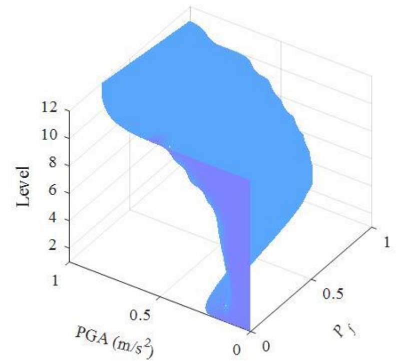
1) For both multistory structure and tall building structure, the story drift rotation decreases gradually along the structure height. The difference of story drift rotation between unidirectional and bidirectional ground motion inputs is larger in lower part of the structures. For the multistory structure, the bottom floor is the weak floor, and for the tall building structure, the 2nd and 3rd floors are weak floors.

2) For both multistory structure and tall building structure, the structural vulnerability under bidirectional inputs is obviously high than that under unidirectional inputs. Along the height of structure (from the bottom to the top), the probability to each limit state decreases.

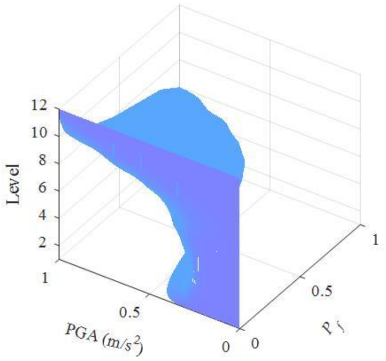
3) For some floors of the structure, not all the damage corresponding to 4 limit states occurs. Usually, moderate and severe damage occur in the lower part of the structure and in the upper part of the structure moderate and severe damage may not occur.



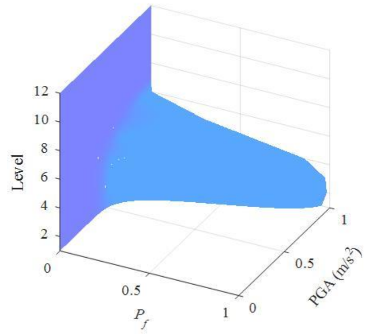

(a) LS1




(b) LS2




(c) LS3




(d) LS4

Fig. 4 The fragility for each floor of GC1.5X

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