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IMPROVED ADAPTIVE SPECTRA-BASED PUSHOVER ANALYSIS FOR ESTIMATING SEISMIC PERFORMANCE FOR BRIDGE STRUCTURES

LIU Chun-guang[1], QIN Si-feng[2], LIN Gao[3]

ABSTRACT

The traditional pushover analysis procedures are based on the invariant force distributions, but none of the invariant force distributions can account for the contributions of higher modes to response. Although the adaptive spectral-based pushover analysis (ASPA) procedure can study the effect of higher modes and considers the dynamic properties of the structures, it is conceptually complicated and computationally demanding for routine application in structural engineering practice. In this paper, an improved adaptive spectra-based pushover analysis (IASPA) procedure which can be employed to analyze practice bridge structures is put forward and proposed. And the seismic performance determined by IASPA is compared with pushover analysis using two force distributions in FEMA-274 and nonlinear RHA procedures. The results indicate that IASPA method provides more superior accuracy in estimating seismic performance on bridge structures.

Keywords: Pushover; Bridge; Seismic performance; Inelastic response spectrum.

INTRODUCTION

The nonlinear static procedure (NSP) or pushover analysis is widely used as a simplified method for estimating seismic performance for structures now. While nonlinear response history analysis (RHA) is the most rigorous procedure to compute seismic demands, it's complicated for analysis and computing, and its computational result is difficult to deal with. And some problems need to be solved in the theory (e.g. the given ground motion being not assured). Therefore nonlinear RHA procedure is not used widely in structural engineering practice (YANG Pu et al. 2000; LI Leng and YE Liao-yuan 1999). The pushover analysis procedure can estimate seismic performance of structures more exactly and simply. And the pushover analysis is written into ATC-40, FEMA-273 and FEMA-274 in the U.S.A., and the Building Standard has been revised into a performance-based design format in Japan. Pushover analysis has also been introduced in Chinese new building structure seismic design criterion (HOU Shuang and OU Jin-ping 2004).

However, none of the invariant force distributions can account for the contributions of higher modes to response, or for a redistribution of inertia forces because of structural yielding and the associated changes in the vibration properties of the structure. To overcome these limitations, several researchers have proposed adaptive force distributions that attempt to follow more closely the time-variant distributions of inertia forces (Fajfar P and Gaspersic P 1996; Bracci JM et al. 1997; Balram Gupta et

[1]Professor, State Key Laboratory of Coastal and Offshore Engineering / Earthquake Engineering Research Division, Dalian University of Technology, Dalian, 116085, China.
[2]PhD student, Earthquake Engineering Research Division, Dalian University of Technology, Dalian, 116085, China, Email: dlutbridge@yahoo.com.cn, qsifeng@hotmail.com.
[3]Professor, Earthquake Engineering Research Division, Academicians of CAS, Dalian University of Technology, Dalian, 116085, China.

al. 2000; LIU Chun-guang et al. 2005). These adaptive force distributions may provide better estimates of seismic performances.

In this paper, an improved adaptive spectra-based pushover analysis (IASPA) procedure based on structural dynamics theory is proposed. IASPA method retains the conceptual simplicity. And it has more superior computational attractiveness compared with the procedure with invariant force distribution in now common analysis. In order to demonstrate its efficiency, four typical ground motion records are selected for estimating seismic performance of bridge structures by IASPA. The seismic demands determined by IASPA are compared against other pushover analysis using two force distributions in FEMA-274 and some significant results are gotten.

IMPROVED ADAPTIVE SPECTRA-BASED PUSHOVER ANALYSIS

The main differences between adaptive spectra-based pushover analysis (ASPA) and the traditional pushover analysis are (1) ASPA uses site-specific spectra to define the loading characteristics, and (2) the applied load pattern continually changes depending on the instantaneous dynamic properties of the system compared to the invariant load pattern used in traditional pushover analysis. That is to say, although the whole load pattern is static it reflects the dynamic properties of the response of the structure. And it reflects the coupling effect between the structure and the properties of frequency and spectra of the earthquake. Considering the coupling between modes arising from yielding of the structure, the accuracy of ASPA is improved greatly, but it also leads to the method being computationally complicated for routine application in structural engineering practice. In this paper, an improved adaptive spectra-based pushover analysis (IASPA) procedure is presented based on ASPA by neglecting the coupling effect between the modes. It retains the excellence of ASPA and simplifies calculation. Therefore, it is much easier to apply to engineering practice.

Assumptions and approximations of the improved adaptive spectra-based pushover analysis

The uncoupled modal response history analysis (UMRHA) procedure was presented by researchers and the coupling effect in the modes was studied (Anil K. Chopra and Rakesh K. Goel 2002). The approximate solution by UMRHA is compared with the ‘exact’ solution by non-linear RHA. The study result indicates that the coupling effect in modes is slight, even for very intense excitation, the errors in either response quantity are only a few percent (Anil K. Chopra and Rakesh K. Goel 2002; Anil K. Chopra and Rakesh K. Goel 2001). Therefore, the paper develops an improved adaptive spectra-based pushover analysis based on UMRHA. Its assumption is: neglecting the coupling in modes arising from yielding of the structure.

Basic steps of the improved adaptive spectra-based pushover analysis

1) Compute the damped inelastic response spectrum for the site-specific ground motion.
2) Initialize the node displacements, node drifts, node shears and stiffness.
3) Compute the periods and modes at the current stiffness state of the structure. Using the node weights (concentrated masses) and the computed eigenvalues, determine the modal participation factors as given by the following expression:

$$\Gamma_j = \frac{1}{g}\sum_{i=1}^{i=N} W_i \phi_{ij} \tag{1}$$

Where:

Γ_j is modal participation factor for j^{th} mode

ϕ_{ij} is mass normalized mode shape value at i^{th} level and j^{th} mode

W_i is weight of i^{th} node

g is acceleration due to gravity

N is number of concentrated masses

Note that equation (1) has been normalized so that $\sum W\Phi^2 = 1$.

4) Compute the node forces at each node level for each of the n modes which are included in the analysis using the following relationship:

$$F_{ij} = \Gamma_j \phi_{ij} W_i S_a(j) \tag{2}$$

Where:

F_{ij} is lateral node force at i^{th} level for j^{th} mode ($1 \le j \le n$)

S_a is spectral acceleration corresponding to j^{th} mode

5) Compute modal base shears V_j:

$$V_j = \sum_{i=1}^{i=N} F_{ij} \tag{3}$$

6) Combine modal base shears using SRSS to compute building base shear V as shown below:

$$V = \sqrt{\sum_{j=1}^{N} V_j^2} \tag{4}$$

7) The node forces computed in Step 4 are uniformly scaled using the scaling factor S_n indicated below:

$$S_n = \frac{V_B}{N_s V} \tag{5}$$

Where:

V_B is the base shear estimate for the entire structure and N_s is the number of uniform steps over which the base shear is to be applied.

Then the lateral force of each node is:

$$\overline{F_{ij}} = S_n F_{ij} \tag{6}$$

8) Take a static analysis of the structure using the scaled incremental story force $\overline{F_{ij}}$ for j^{th} mode computed in the previous step.

9) Compute node displacements, node drifts and node shears corresponding to the scaled incremental node force $\overline{F_{ij}}$ for j^{th} mode and add these to the same from the previous step.

10) At the end of every cycle, compare the accumulated story forces with their respective yield values. If any element has yielded, re-compute the member and global stiffness matrices and return to Step 3.

11) Repeat the above process until either the maximum base shear is reached or the global drift exceeds the specified limit.

12) Repeat Steps 2 to 11 for as many modes as required for sufficient accuracy. Typically, the first two or three modes will suffice.

13) Determine the total response by combining the peak responses (including peak node displacements, peak node drifts, peak node shears for every mode) using the SRSS combination rule.

TWO LATERAL FORCE DISTRIBUTIONS IN TRADITIONAL ANALYSIS

In this paper, the seismic performance determined by IASPA is compared with pushover analysis using two lateral force distributions in FEMA-274 (FEMA 1997) those are linear distribution and uniform distribution.

1) Linear distribution: It is often suggested in building codes, considering that the structure is subjected to a linear distribution of the acceleration throughout the building height. The force increment ΔF_i at each step for story i is calculated according to:

$$\Delta F_i = \frac{W_i h_i}{\sum_{j=1}^{N} W_j h_j} \Delta V_b \tag{7}$$

Where:

W_i and h_i are the story weight and the story elevation, respectively, ΔV_b is the increment of the building base shear, and N is the number of the stories.

2) Uniform distribution: The lateral force of every story has direct ratio with the story weight, and the force increment ΔF_i at each step for story i is calculated according to:

$$\Delta F_i = \frac{W_i}{\sum_{j=1}^{N} W_j} \Delta V_b \tag{8}$$

Where:

W_i is the story weight and ΔV_b is the increment of the building base shear, and N is the number of the stories.

THE SELECTED TYPICAL GROUND MOTION RECORDS

To demonstrate the applicability of the improved adaptive spectra-based pushover analysis, four typical ground motion records are selected in the paper that are Northridge ground motion (1994), Taft ground motion (1952), El Centro ground motion (1940) and Tianjin ground motion (1976). The selected ground motion records are fit for middling period structures (0.5~1.5s) for Ⅰ type of site soil, Ⅱ type of site soil, Ⅲ type of site soil, and Ⅳ type of site soil respectively (China Association for Engineering Construction Standardization 2004). The inelastic acceleration spectra (5% damped, μ_Δ =5) of four ground motion records whose maximum value are normalized are shown in Figure 1.

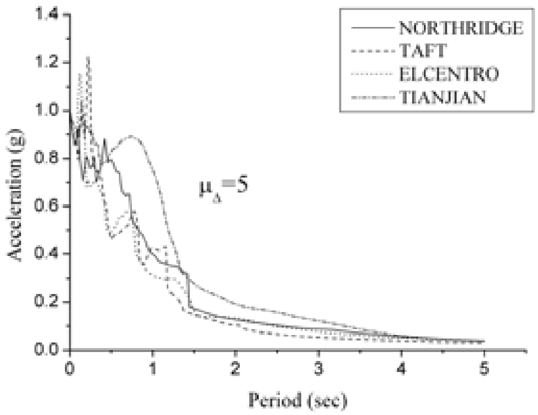


Figure 1. The inelastic acceleration spectra (5% damped) of four ground motion records

ANALYSIS OF AN ACTUAL BRIDGE STRUCTURE

The bridge structure example selected in this paper is a continuous girder bridge with reinforced concrete single column pier. The pier selected in the paper is the secong pier of the first span. The length of the bent is 100m and the width is 8.8m. Perfusion stakes are used as infrastructures and the concrete grade of the pier is C30. The section of the pier is rectangular, and the computing height of the pier is 23.144m. The factor of displacement ductibility (FAN Li-chu and ZHUO Wei-dong 2001) was obtained by calculation: $\mu_\Delta = 5$. The structure of the pier and the model of calculation are shown in Figures 2 and 3 (WANG Dong-sheng et al. 2000; R. E. Valles et al. 1996). And the section parameters are shown in Table 1.

Table 1. The Parameter Table of Rectangular Sections of Piers

Column element type number	Element height (mm)	Section Size D×B (mm×mm)	Protection layer thickness (mm)	Longitudinal steel arrangement (D)	Longitudinal steel arrangement (B)	Hoop bar arrangement
1	3159	2800×2400	30	27Φ32	21Φ32	ϕ12@15
2	2000	2846×2400	30	27Φ32	21Φ32	ϕ12@15
3	2190	3219×2400	30	27Φ32	21Φ32	ϕ12@15

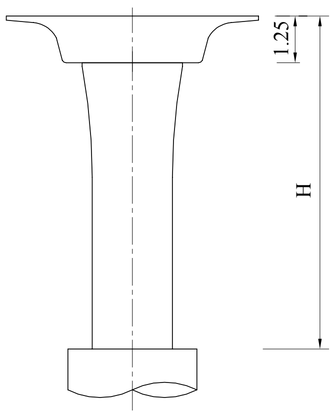


Figure 2. The structure of piers (m)

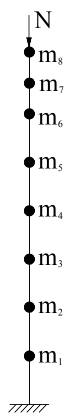
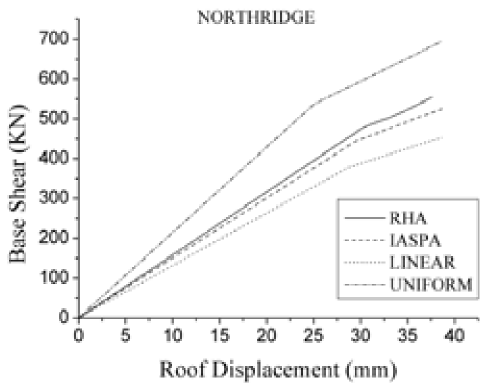
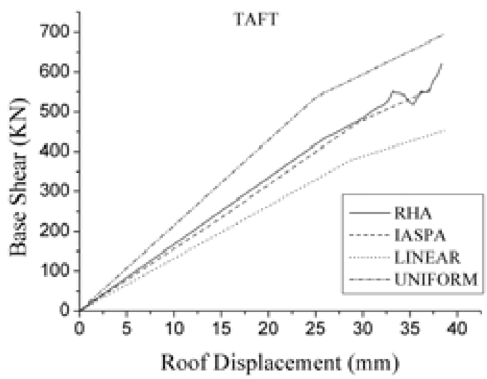


Figure 3. The calculation model

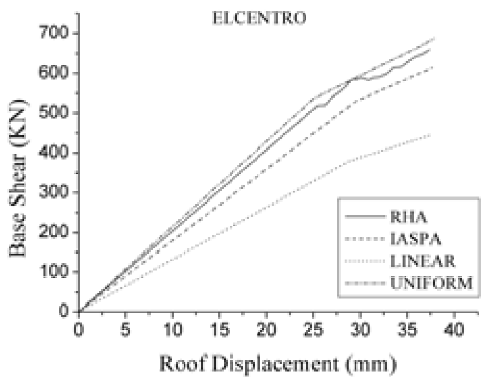
The capacity curve is the important result obtained by pushover analysis. The selected structure in the paper is performed pushover analysis by using three methods that are linear distribution, uniform distribution and improved adaptive spectra-based pushover analysis. Increase the peak acceleration value of the ground motion gradually, and calculate the maximal roof displacement and maximal base shear under every peak acceleration value to obtain one dot on the capacity curve (WEI Wei 2001). Then we can get the capacity curve by RHA. The relationship curves between roof displacement X_t and base shear V_b (capacity curve) obtained by three pushover analysis methods are compared with capacity curves obtained by nonlinear RHA for four typical ground motion records. Figure 4 shows the comparative results.



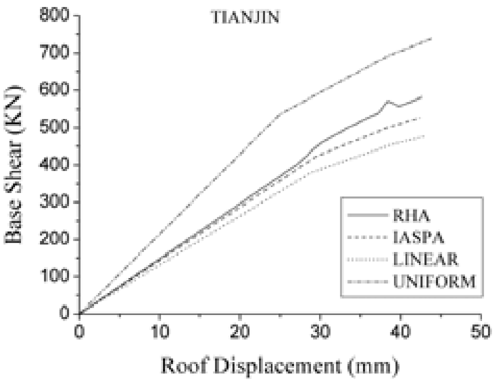
A. Capacity curve (Northridge)



B. Capacity curve (Taft)



C. Capacity curve (Elcentro)

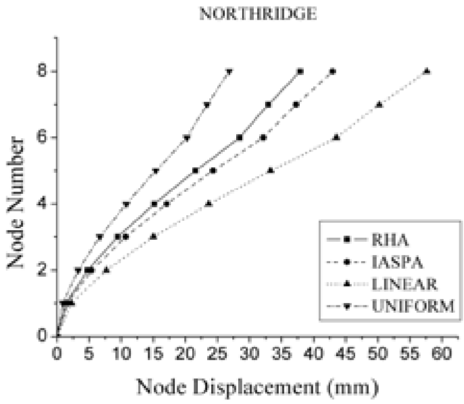


D. Capacity curve (Tianjin)

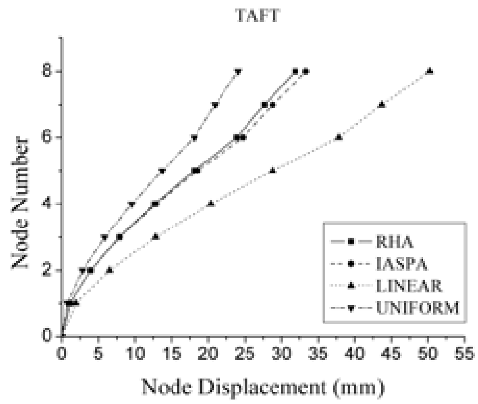
Figure 4. The capacity curve comparison of bridge structure

In Figure 4, it is easy to see that the capacity curves of the structure obtained by using linear distribution and uniform distribution have large errors compared against the results by RHA. But the improved adaptive spectra-based pushover analysis provides superior accuracy because it uses response spectra to define the properties of load. Therefore, to select a reasonable lateral force distribution mode is the most important step in the process of pushover analysis.

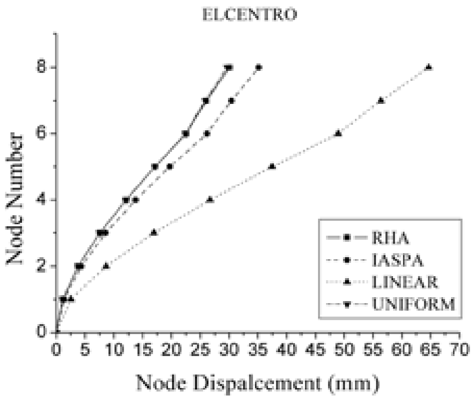
Pushing the selected pier by using a kind of lateral load pattern, to increase the lateral force value gradually, and to repeat the process of nonlinear static analysis until the maximum base shear of the pier is reached, then we can get the maximum node response values of the pier. The maximum node displacements, node drifts and node shears obtained by using two FEMA load patterns, IASPA and RHA under four typical ground motions respectively are shown in Figure 5. We can see that the difference between the response predicted by FEMA pushover analyses and RHA is great. The proposed improved adaptive spectra-based pushover analysis, however, predicts response reasonably well as evident in the plots shown in Figure 5.



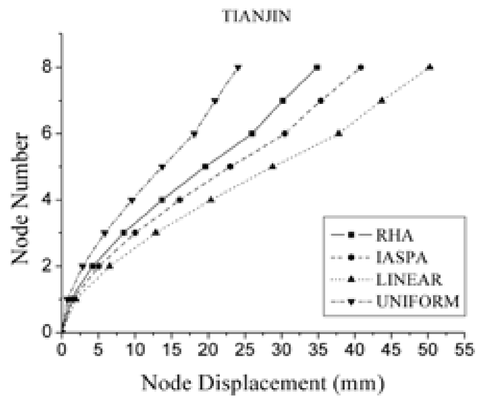
A. Node displacements (Northridge)



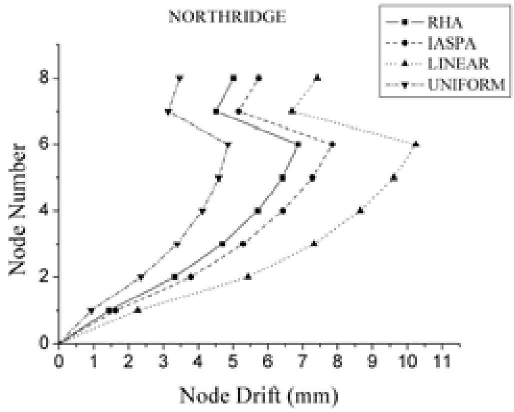
B. Node displacements (Taft)



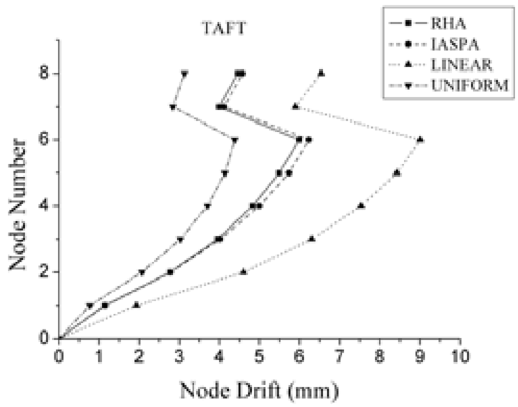
C. Node displacements (Elcentro)



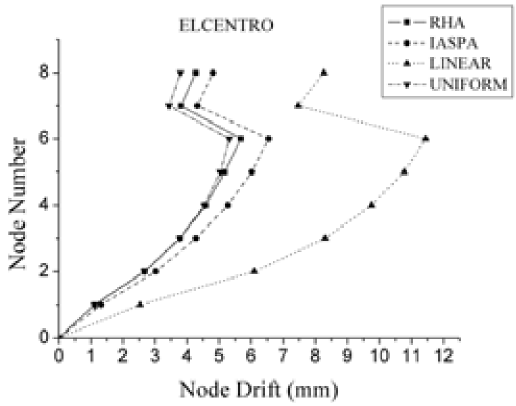
D. Node displacement (Tianjin)



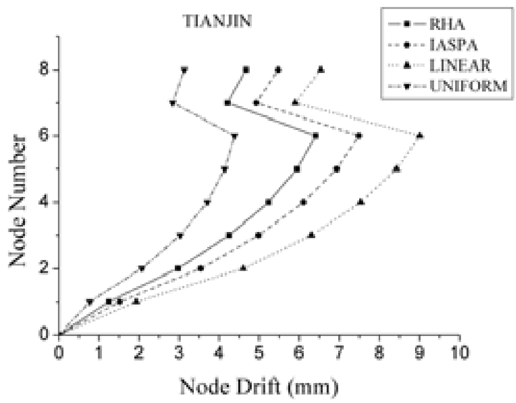
E. Node drifts (Northridge)



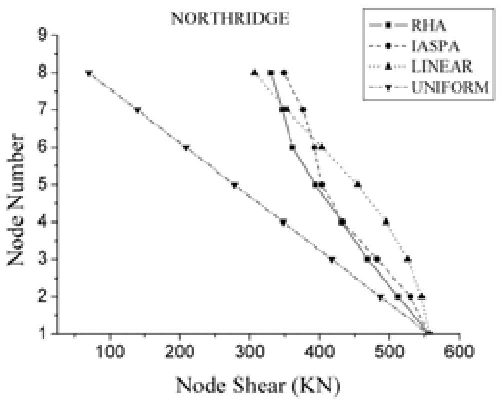
F. Node drifts (Taft)



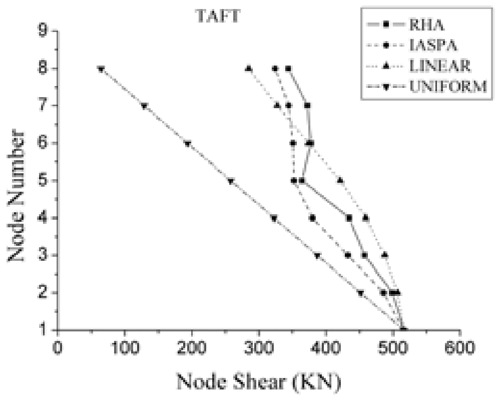
G. Node drifts (Elcentro)



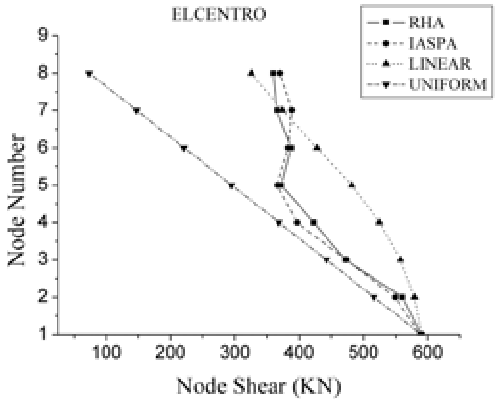
H. Node drifts (Tianjin)



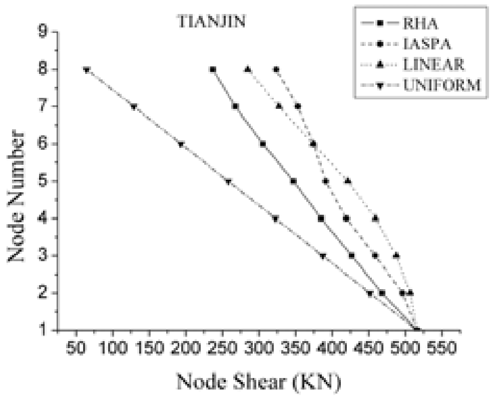
I. Node shears (Northridge)



J. Node shears (Taft)



K. Node shears (Elcentro)



L. Node shears (Tianjin)

Figure 5. The node response values comparison for the bridge pier for selected ground motions

CONCLUSIONS

The aims of the studies in this paper are to develop an improved adaptive spectra-based pushover analysis procedure which retains the conceptual simplicity and superior accuracy. And it is also compared with the linear and uniform pushover analysis methods. The following conclusions are gotten.

1) Because the response spectra are employed directly to define loading characteristics and the force increment of every step is based on the instantaneous dynamic property of the structure in this IASPA method, the capacity curve and maximum node response values obtained are closer to the real response values of the bridge structure compared with linear and uniform pushover methods.

2) Compared with adaptive spectra-based pushover analysis, the improved adaptive spectra-based pushover analysis neglects the coupling in modes arising from yielding of the structure, so it is more simple and convenient for calculation. And it uses inelastic response spectrum instead of elastic spectrum, so it is accurate enough for practical application in bridge structure evaluation and design.

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