A New Approach for Consideration of Earthquake Low Cycle Fatigue Phenomena on Reinforced Concrete Frames

A.Bakhshi and B.Keshavarzi

Civil Eng. Department, Sharif University of Technology, Tehran, Iran

SUMMARY:

Many researchers suggest ways for structural design based on performance based design methodology. Most of these methods use assumptions such as domination of first mode for structural behavior , consideration of nonlinear structural behavior by utilizing equivalent damping energy or nonlinear spectra, ignoring strength and stiffness degradation by using elastic perfectly plastic model. In this paper first and third of these assumptions are investigated and their impacts on accuracy is determined.

Earthquakes cumulative damage effect has come under scrutiny recently. In this paper a suggested method for considering this effect is investigated and all of its advantages and disadvantages are discussed and its deficiencies are obviated by suggesting some modifying solution.

Keywords : Performance based seismic design, Earthquake input energy, Hysteretic Energy, Repeated cycle

1.INTRODUCTION

After the occurrence of Northridge 1994 and Kobe 1995 earthquakes, seismic design methods were modified. This modification was due to structural and nonstructural damage observed in buildings. Following these two great events, philosophy of performance based design that considered different performance level for different hazard levels was suggested. The following defects are related to force based design methodology:

1) According to experiences from recent earthquakes, structures designed by force method didn't perform uniformly. In addition to this, providing life safety goal may lead to huge economical loss.

2) Benefiting from some simplifying assumptions about displacement shape profile, dominant period and ductility lead to an inexact force which will be used for seismic design. This force is known as base shear.

3) In the last three decades, it has been shown that increasing strength of a structure doesn't necessarily increase the level of life safety, reliability or damage reduction. Generally in current force based design methodology the structural behavior assessment index is strength and it is contrary to structural real behavior in nonlinear manner which is governed by displacement. In nonlinear displacement domain which is the result of severe earthquakes, structural force variation is small.

4) The assumptions about nonlinear performance of structures and approximating that with elastic characteristics such as initial stiffness are not an exact method. For RC frames and masonry buildings initial stiffness never return after first yield.

Considering all the above mentioned deficiency, Performance based design was suggested and some codes like FEMA 356 [1] and ATC40 [2] offered methods for this newly developed procedure.

1.1. Performance Based Design

Most of codes and researchers that deal with performance based design use following assumptions in their design procedure:

1) Approximating structural displacement profile in height by its first vibrational mode shape. This assumption arises from pushover analysis which is done only for first mode. For high rise building imposed with near fault seismic excitation finding effective modes isn't an easy task and according to Krawinkler the ductility demand trend varies for stories in IDA analysis [3] . Sassaki studied the performance of high rise building imposed with earthquake excitation and concluded that for some high rise building higher mode effect is not negligible [4]. It seems that utilizing CSM method which is suggested by Chopra [5] is helpful. This method is originally for finding structural ductility demand for known frames and earthquake records but it can be used for finding structural ductility demand for different modes. Comparing these ductility demands is a key factor for finding effective modes. In the following tables accuracy of this suggestion is verified by Sassaki's results.

Tabel 1.1.Demand ductility for 12 story frame imposed by Sylmar earthquake

Mode No.	CSM demand ductility	Sassaki demand ductility
1	1.4	1.402
2	2.5	2.42
3	1	0.88

Tabel 1.2.Demand ductility for 17 story frame imposed by Coyote lake earthquake

Mode No.	CSM demand ductility	Sassaki demand ductility
1	1	0.73
2	1.2	1.17
3	1	0.47

It is seen that for 17 stories frame building, second mode is dominant and the location and quantity of cracks show well compatibility with second mode shape. It is also observed that Chopra's method may predict dominant mode with great accuracy. In the following, this method is considered for demand prediction.

2) In most current procedures, ductility or other correlated parameters like allowable plastic hinge rotation is guessed at first stage and by finding equivalent damping and using trial and error, modal displacements are determined. These methods utilize the concept of ATC40 that compute modified damping by finding maximum structural displacement [2]. Chopra showed that for some structural systems the procedure doesn't converge to its exact value [6]. In addition to this, equating hysteretic and damping energy that are based on displacement and velocity respectively is theoretically wrong.
Some researchers like Chopra benefit from nonlinear demand spectra that is developed by relation between R-μ-T in order to better assess structural performance [6]. Although it may be seen as advancement, it has an inherent assumption about equal ductility of MDOF and SDOF. This assumption imposes high ductility demand on some MDOF members.

3) Researchers usually don't pay attention to structural member's behavior model and use elastic perfectly plastic (EPP) model for simplicity. It is shown that RC members decrease their strength and stiffness in cyclic loading. These defects may be best shown by considering artificial records possess pulses that are exerted in an increasing level of period .Comparing input energy of EPP model and Clough model shows significant importance of strength and stiffness degradation. In figure1.1 the period of first pulse is 1 sec and the period of next pulses would be 2,3,4 and 5 sec.

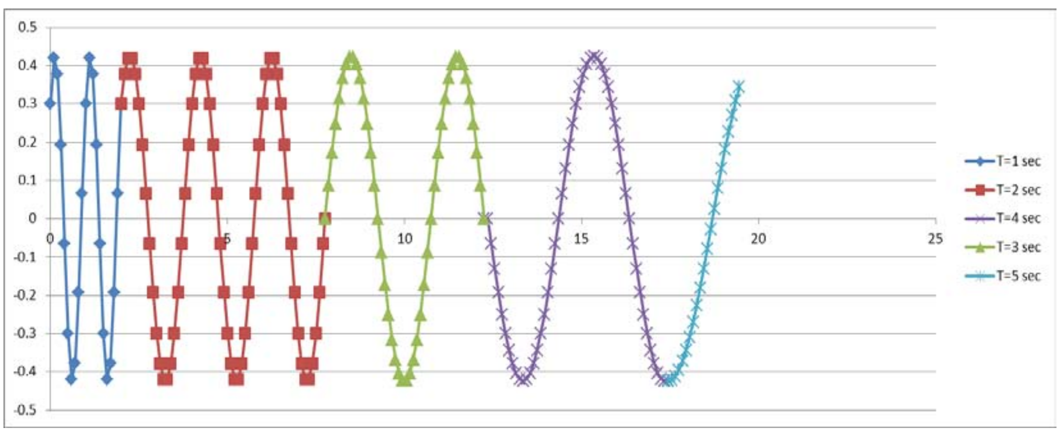

Figure 1.1. Artificial record with initial excitation time of 2 sec and 1 sec increment for dominant period

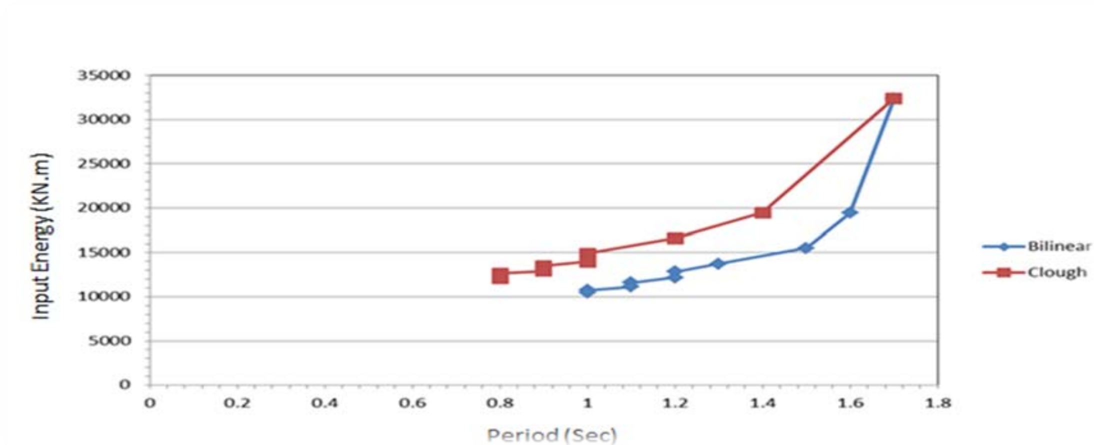

Figure 1.2. Maximum input energy for different ductility for bilinear and Clough model for the above mentioned artificial record

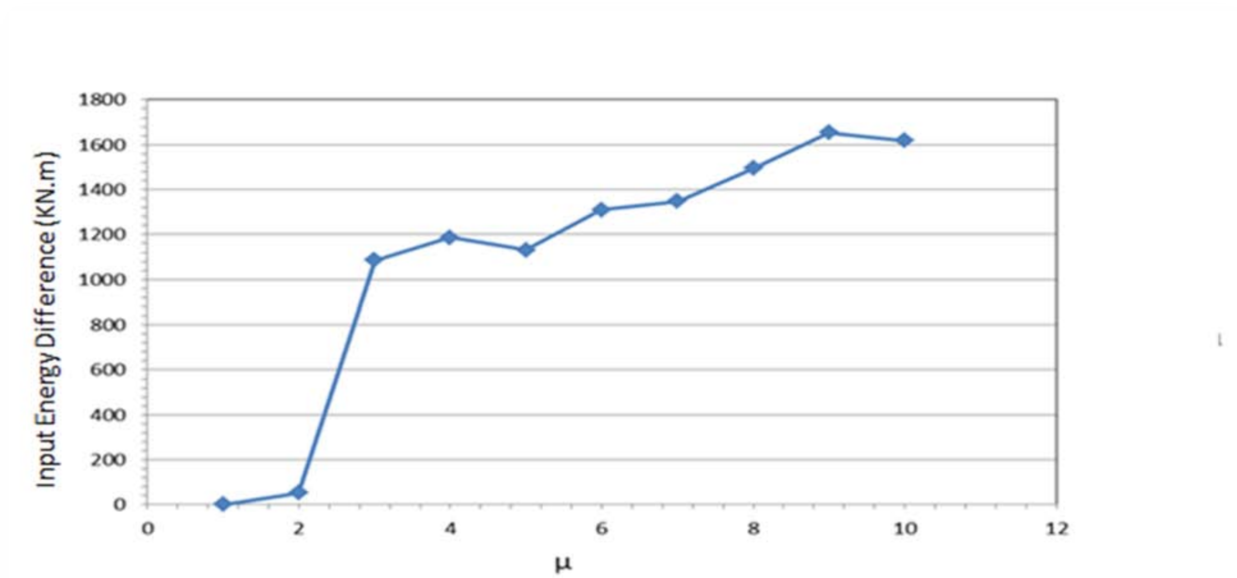

Figure 1.3. Difference between input energy of two structural models versus ductility for the above mentioned artificial excitation

Selecting artificial record offer a suitable chance to observe the difference between behavior of two models. In figure 1.2 it is obvious that for equal input energy, Clough model always needs more initial stiffness than bilinear model. It is also shown that for same period Clough model always input higher energy than bilinear model. Position of peak point of input energy moves to down and left by increasing ductility demand. All of the mentioned behavior is just because of resonance. This phenomenon enforce Clough model to increase its initial stiffness in order to elevate the chance of equivalent frequency between structural model and input motion.

2.RESEARCH METHOD

It is important to note that this paper investigates a proposed procedure that suggests a method for considering earthquake repeated cycles effect on RC frames [6]. At the first step 5 frames from 4 to 9 stories are designed according to Iranian national building code [7]. For the next step, vertical load combination of 1.1D+0.9L is exerted on all the beams of the stories. In this step, pushover analysis is done for first three modal shapes of the frames by keeping vertical load constant at each loading step. In pushover analysis for different modes, frame is pushed until all stories reach their maximum resisting shear and start to fail until reaching zero shear. Frames equivalent period and ductility could be easily extracted by using bilinear procedure mentioned in FEMA356 [1]. In this paper plot of $\emptyset_n^T M \emptyset_n s$ versus $\emptyset_n^T MV$ is used for finding structural properties.$M\emptyset_n s$ is lateral load at each step of pushover analysis and v is frame's displacement profile at each loading steps. Finding equal properties might be done by using base shear versus roof displacement plot. The first one is better than the second because the later doesn't consider some events in higher modes .This shows itself in Table 3 and differences between natural periods and ductility predicted by these two methods.

Table 2.1. Frequency, Period and ductility for different frames obtained by QV and VD diagram

Frame	Mode No	Graph	Ω (rad/sec)	T (sec)	μ
4 Story	1	QV	8.815	0.712	1.241
		VD	7.445	0.843	1.225
5 story	1	QV	6.439	0.975	2.059
		VD	6.037	1.04	1.937
6 story	1	QV	6.27	1	3.465
		VD	6.155	1.02	3.563
	2	QV	15.498	0.405	2.269
		VD	12.384	0.507	3
	3	QV	25.99	0.241	4.175
		VD	10.587	0.593	2.772
7 story	1	QV	6.178	1.016	4.305
		VD	5.994	1.047	3.981
	2	QV	14.426	0.435	5.996
		VD	12.043	0.521	8.777
	3	QV	24.14	0.26	3.54
		VD	18.4	0.341	7.464
8 story	1	QV	4.794	1.309	1.784
		VD	4.674	1.351	1.705
	2	QV	11.906	0.527	1.874
		VD	9.269	0.677	2.319
	3	QV	19.594	0.32	2.917
		VD	18.188	0.345	8.5

In Table 2.1 QV represent for generalized force and displacement and VD stands for base shear versus roof displacement. For next step, knowing absorbed energy in pushover analysis and using FajFar assumption [8] lead to following equation for energy distribution in stories.

$$\psi_{n,i} = \frac{E_{hmn,i}}{\sum_{i=1}^{Number\ of\ Stories} E_{hmn,i}} \tag{2.1}$$

In which $E_{hmn,i}$ is hysteretic energy that is absorbed by the i^{th} story until any story in that mode start to reduce its lateral load capacity under monotonic loading of n^{th} mode.

Using Uang's assumption for obtaining MDOF energy from equivalent SDOF energy [9], we can find hysteretic energy that is absorbed by i^{th} story by the following equation. In this equation r is the number of desired mode and is equal to 2 in this paper.

$$E_{hi} = \sum_{n=1}^{r} \psi_{ni} \Gamma_n^2 \, E_{hn}^{sdof} \tag{2.2}$$

In the suggested procedure E_{hn}^{sdof} is obtained by using Deccani and Mollaioli's spectra [10]. These spectra are developed by using EPP model for SDOF system. Previously it is shown that using model like EPP that couldn't consider strength and stiffness degradation imposed great uncertainty in the solution procedure and because of this, using these spectra mayn't be acceptable.

$$E_I = f_A(\mu, T) A E_I, E_h = f_h(\mu, T) E_I \xrightarrow{yields} E_h = f_A f_h A E_I \tag{2.3}$$

$$E_{hi} = \sum_{n=1}^{r} \psi_{ni} \Gamma_n^2 f_A f_h \, A E_I \tag{2.4}$$

In the suggested procedure, the author use μ and T that are extracted from pushover analysis and substitute it into the hysteretic spectra in order to calculate energy related to predefined damage index [6]. A deficiency about this method is about using monotonic ductility as an ultimate ductility in defined spectra for gaining maximum hysteretic energy. This procedure is valid only for static case in which reaching the ultimate static ductility μ_{mon} means gaining maximum possible hysteretic energy. In dynamic analysis owing to strength and stiffness degradation, collapse occurs before reaching μ_{mon} . It seems that finding a ductility that is related to predefined damage index isn't a simple task and need lots of effort because of governing nonlinear equations. Finding damage index spectra needs a function that incorporate period, ductility and damage index as independent parameters.[11]

The basic assumption in the proposed procedure is about the constant ratio of hysteretic energy for a defined damage index to absorbed energy in pushover analysis. This constant ratio is called A factor.

$$A = \frac{E_{hi}}{E_{hmn}} \tag{2.5}$$

In fact, equation 2.5. is the second part of the Park & Ang equation for damage index. [12] The assumption about A factor is valid only if the first part of the equation is constant for different records. According to Katsanos.et.al [13] this would be valid only for records that are fitted into a spectra by the way of optimization process.

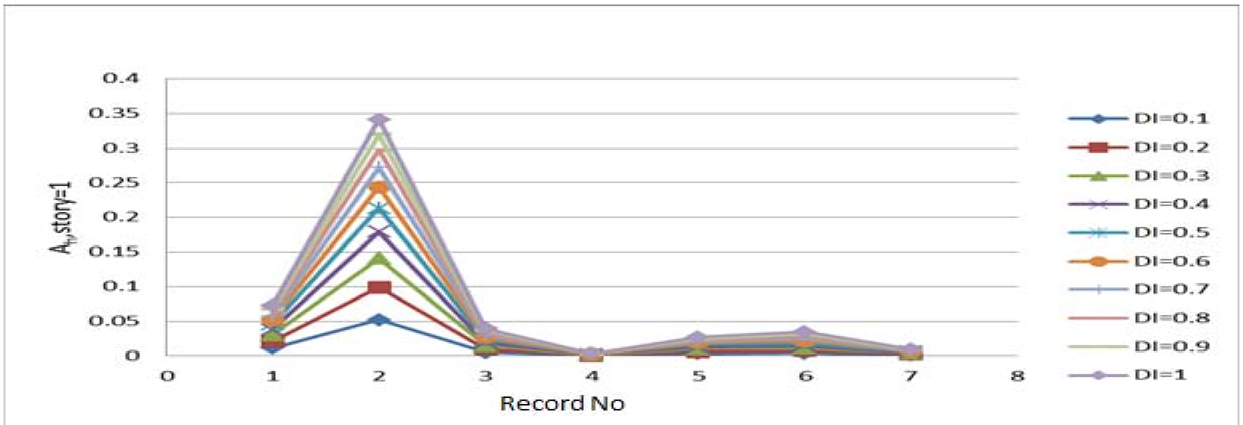

Figure 2.1. Variation of A factor for first story of 4 stories frame for 7 unmodified records on Soil Type A

Table 2.1.Coeeficient of variation (COV) for A factor for first story of 4 story frame-Soil Type A

		Unmodified records							
COV	DI	Story1	Story2	Story3	Story4	Story1	Story2	Story3	Story4
	0.1	1.547	1.547	1.547	1.547	0.389	0.389	0.389	0.389
	0.2	1.54	1.54	1.54	1.54	0.39	0.39	0.39	0.39
	0.3	1.522	1.522	1.522	1.522	0.391	0.391	0.391	0.391
	0.4	1.519	1.519	1.519	1.519	0.391	0.391	0.391	0.391
	0.5	1.509	1.509	1.509	1.509	0.391	0.391	0.391	0.391
	0.6	1.499	1.499	1.499	1.499	0.392	0.392	0.392	0.392
	0.7	1.49	1.49	1.49	1.49	0.392	0.392	0.392	0.392
	0.8	1.482	1.482	1.482	1.482	0.393	0.393	0.393	0.393
	0.9	1.475	1.475	1.475	1.475	0.393	0.393	0.393	0.393
	1	1.468	1.468	1.468	1.468	0.393	0.393	0.393	0.393

It is found that A factor variation follow Fourier amplitude variation for a defined period. This trend could be easily explained by the following formula in which E_I is elastic input energy for an arbitrary frequency ω and $F(\omega)$ is the amplitude of Fourier transformation for this predefined frequency.

$$E_I = \frac{1}{2} m F(\omega)^2 \qquad (2.6)$$

It is obvious from the above formula that any record with higher Fourier amplitude exert higher amount of energy into the structure. This equation is acceptable for nonlinear behavior.

$$E_{h,i} = a_{hi}E_{hmi} = a_{hi}\left(E_{hm,i}^{max} + E_{hm,i}^{min}\right) = 2a_{hi}E_{hm,i}^{-} = 2a_{hi}b_{hi}E_{hm,i}^{max} \tag{2.7}$$

$$AE_I^{final} = \min\{AE_I^{final}\} \tag{2.8}$$

By considering minimum AE_I in reality all the stories weakness are taken into account and this method may somehow be a solution for difficulties that arises from selecting ductility by the proposed nonlinear spectra.

One of the big deficiencies of the proposed procedure is about utilizing AE_I . This parameter is the square under the earthquake elastic input energy between the period of 0.05 and 4 sec. According to equation (6-2) it is clear that this parameter has an obvious relation with earthquake Fourier spectra between the mentioned thresholds. If we mirror any input record with an axis that is perpendicular to horizontal axis at the center point, a new record would be obtained which is called modified record (Figure 2.2). These two records have same Fourier transformation spectra and consequently same AE_I but their elastic and inelastic spectra are totally different (Figure 3.2). One of the disadvantages about Fourier transformation is about its inherent disability in time domain and this disadvantage shows itself very well in this example.

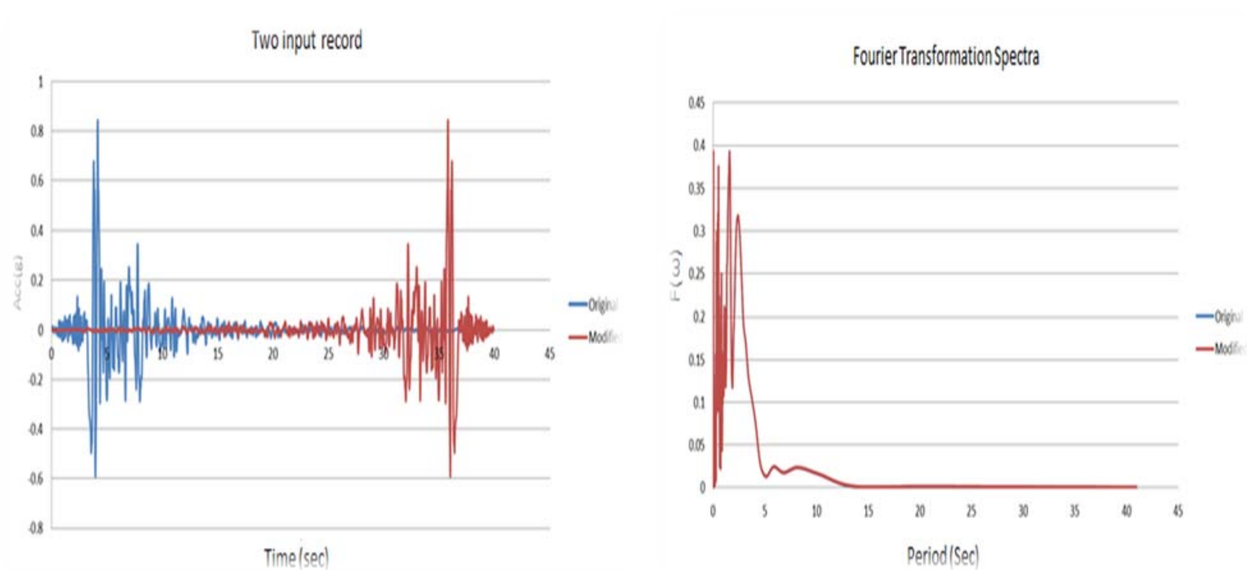

Figure 2.2. Two input records (Left) and their Fourier transformation spectra (right)

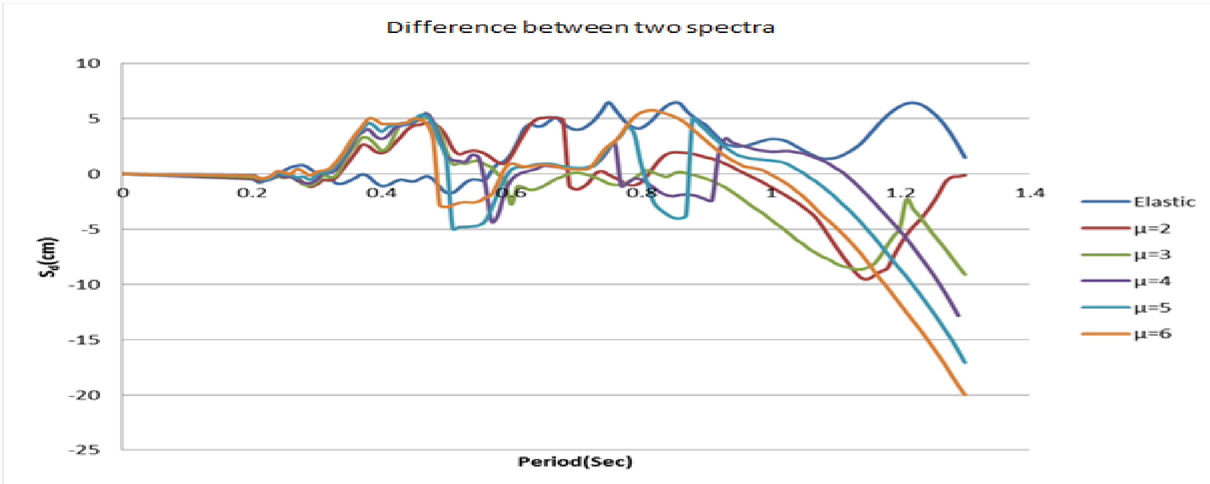

Figure 2.3.Differences between displacement spectra of the two records

3.CONCLUSIONS

In this article a method for considering earthquake repeated cycle on the performance of RC frames was investigated. It was shown that using the first two fundamental modes of vibration without any assumptions and taking into account stories deficiency by benefiting the minimum AE_I are two important advantages of this method. Using energy spectra that were developed by EPP model and substituting monotonic ductility in predefined spectra in order to obtain the maximum possible hysteretic energy are the two main disadvantages of the suggested method. In addition benefiting Chopra's modified CSM method for solving modes selection problem may be helpful.

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