Comp. Meth. Civil Eng., Vol. 3, 2 (2012) 79-91

CMCE
Computational Methods in Civil Engineering

Evaluating the effects of near-field earthquakes on the behavior of moment resisting frames

Vahid Sharif[a], Farhad Behnamfar[b] *

[a]*Department of Structural Engineering, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran*
[b]*Department of Civil Engineering, Isfahan University of Technology, Esfahan 8415683111, Iran*

Received 14 July 2012; accepted in revised form 24 August 2013

Abstract

Following the 1994 Northridge and 1995 Kobe earthquakes, most of modern structures damaged seriously or devastated totally despite the seismic codes of these countries that had been expected to bear advanced criteria for seismic design of structures. After extensive research, the most probable reason of those destructions was attributed to special specifications of near-field earthquakes. In this paper, in addition to a brief review on the special characteristics of near-field earthquakes, using actual records of these ground motions and pulse-like inputs simulating near-filed records, the effects of this type of earthquakes on the distribution of the maximum shear force and flexural moment demands are evaluated. Results show that the response is very sensitive to the ratio of natural period of structure to the governing period of ground shaking pulse, such that, in some cases it leads to increasing force demand ratios of structure and even transmitting its centroid to upper stories.

Keywords: Near-field earthquake, Seismic behavior, Moment frame, Force demand.

1. Introduction

Near-field ground motions are earthquakes that occur less than 15 km from the site under consideration. In this type of earthquakes, the Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Peak Ground Displacement frequently exceed 1g, 1.5 m/s and 1 m respectively [1]. Near-field records often have obvious long period pulses that emerge mainly at the beginning of the record and affect the response of structures. Due to the significance of these pulses in the final response of structures, new procedures have been developed so that not to eliminate these pulses during filtering correction of records [2]. Existence of distinct pulses in the near-field records (sometimes an obvious pulse and other times a combination of few pulses together) causes particular features in the behavior of structures subjected to this type of earthquake that are mentioned as follows:

- Mode-like behavior of structure in which one or more modes in combination determine the final response of structure, converts to wave-like behavior in which the response is determined by adding the effects of passing waves through structure [3].

*Corresponding author.
Tel.: +98(311)3913844 Fax: +98(311)3912700
E-mail address: farhad@cc.iut.ac.ir

- Because of the large amount of energy which is imposed to structure subjected to ground motion pulses, the distribution of nonlinear behavior of structure is altered in such a manner that in lieu of being distributed along the height of structure, most of energy is absorbed by the first hinges and the transmission of energy to other levels is reduced [4].
- In records of these earthquakes, as the PGV/PGA ratio increases, the acceleration-sensitive region (a region in the response spectrum in which spectral acceleration, S_a, is invariant with respect to period) extends and the velocity-sensitive region shortens resulting in some dynamic characteristics such as an increased apparent stiffness, a higher ductility demand restricting the efficiency of the added viscous damping system that has a direct relation with the width of velocity-sensitive region [5].
- Newer research [4,6] has shown that in addition to the value of demand parameters such as displacement, strength and ductility, their distributions are also a function of the ratio of natural period of structure, T_n, to governing period of ground shaking pulses, T_p.

In reference [7], more specifications of the near-field ground motions are cited.

The prevailing approaches for depicting behavior of structure subjected to pulse-like ground motions can be classified to two general groups. The first approach tries to simplify the input and the equivalent pulse procedure is one example of this group. In this method, instead of evaluating the structure subjected to actual record of earthquake, the behavior of the structure is evaluated using a simple pulse corresponding to the actual record [3].

The second set of these approaches tries to use a simpler model of structure instead of simplifying the input but in return it considers the propagation of waves more precisely when developing the governing equations of structural behavior. The shear or the generalized shear-flexural beam can be referred to as an example of this group [6&7]. In this method, the main structure is simplified to an equivalent shear-flexural beam and the structural response is determined superposing the passing waves through the structure. For more information in this regard, references [8] can be consulted.

2. Modeling and analysis procedure

In this section, dependency of force demands such as flexural moments and shear forces along the height of structure to the period of pulse is evaluated. Also, for understanding how proportional the governing demand is to the available capacity, the parameter DCR is utilized. This parameter shows demand over capacity ratio for a member and has been utilized extensively in guidelines for evaluation of structures against earthquakes. Three types including 4-, 8- and 12-story buildings are used for analyzing. These structures are designed based on the Standard 2800 [9] and the Iranian code for design of steel structures (10^{th} clause of the National Building Regulations) [10]. The cross sections of structural members are shown in Figure 1. The cross sections of beams and columns are invariant for a given building and are not changed along the structure so that only effects of the pulse period are evaluated. All analyses in this study are conducted in the time domain and are linear consistent with the definition of DCR.

With regard to the effect of propagation of waves on the final response of structures, when a finite-element based software is used for analysis, it is necessary that proper types and meshing of elements to be considered in order to have all important frequencies contribute to the response. To select the optimum size of meshing, the maximum shear and flexural DCR's in the 4-story structure subjected to a simple pulse are calculated by the finite element procedure and a dynamical stiffness matrix method that is cited in reference [11]. The results are compared and the best type of meshing is selected. The dynamical stiffness matrix method is on the basis of calculating the response in frequency domain based on the contribution of all vibration modes using a distributed mass model. It can be considered as a rigorous solution in the linear range. As response of a structure under a near-field earthquake is "Wave-like" rather than "Mode-Like", therefore the element size should be fine enough in order not to miss the higher frequency content of the response that is important in the near-field zone. For this purpose, a distributed mass medium should be provided in the frequency domain to make it possible for all existing waves to pass. In the time domain, this is equivalent to use a fine mesh, i.e. several elements, along a single column or beam. After conducting the above computations and comparing the results, it was decided to use ten elements along each beam and column to gain enough accuracy. The same mesh size is also used for the 8-story and 12-story structures.

Because of similarity between the near-field ground motion pulses and a cosine pulse, this type of pulse is used as an equivalent pulse shown in Figure 2. Each of the structures is subjected to the simple pulse of Figure 2 with periods ranging from smaller to larger than the natural period of structure and the distribution of maximum shear and flexural DCR's along the height of structures are determined. When T_n/T_p <1, where T_n is the fundamental period of building and T_p is the period of pulse (see Figure 2), the response should be strongly influenced by the characteristics (period and amplitude) of the pulse. On the other hand, when T_n/T_p >1, the response is expected to be practically determined by the free vibration properties (period and damping) of building.

For brevity, only the results of 8-story structure are presented here noting that all three types of structures have a similar behavior. Detailed results are available in reference [12]. The common height of each story is 3m and number of bays is 4 with each bay spanning 5m. The fundamental period of the 8-story building is about 1 sec.

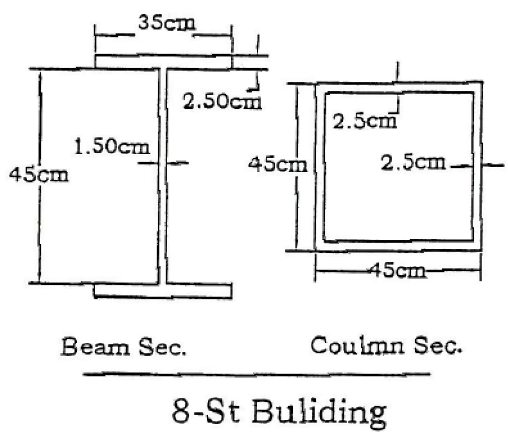

Figure 1. The cross sections of beams and columns of the 8-story building

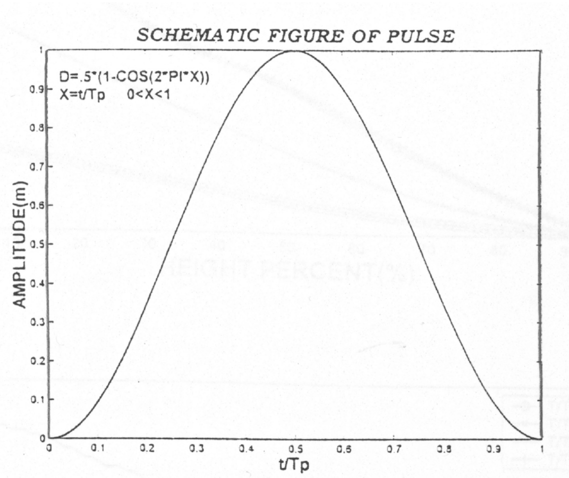

Figure 2. The equivalent cosine pulse

3. Analysis subjected to the simple pulse

3.1. Distribution of maximum shear and flexural DCR's along the height of structure

In this section, the distribution of maximum shear and flexural DCR's under simple pulses with periods varying from shorter to longer than the natural period of the structure are calculated. The results for the 8-story structure are presented in Figures 3 & 4 for interior and exterior columns.

It can be observed that as the T_n/T_p ratio increases, the distribution of maximum shear and flexural DCR's differs from a gradual decrease from the base level to the upper stories to such a manner that sometimes the distribution attains its peak in the upper stories. On the other hand, in Fig. 3, DCR values as large as 15 occurs for the columns. This is due to two different facts. First, the analysis is elastic and no response reduction factor (R) is used. Second, the amplitude of the cosine pulse of Figure 2 used as an equivalent input ground motion was selected to be 1 m that is a very large value and representative of near field earthquakes. For smaller amplitudes, the response will also be smaller.

3.2. Evaluating the distribution of shear and flexural DCR's in beams

The distribution of maximum shear and flexural DCR's along the beams against T_n/T_p is derived using the same pulse of the previous section. The results are presented in Figures 5& 6.

It should be noted that due to symmetry, the results of beams are shown only for a half total beam length (two 5-meter spans). It can be seen in Figures 5 & 6 that as the T_n/T_p ratio increases, the maximum values of shear and flexural DCR's increase especially in the upper stories such that sometimes the maximum values for the upper stories are larger than those of the lower stories.

Also, in Fig. 5b, very large flexural DCR values occur for the beams. The reason is quite similar to what described at the end of Section 3.1 for the columns adding that normally plastic hinges form in beams sooner than columns. Therefore, the maximum DCR's should be larger in beams than in columns.

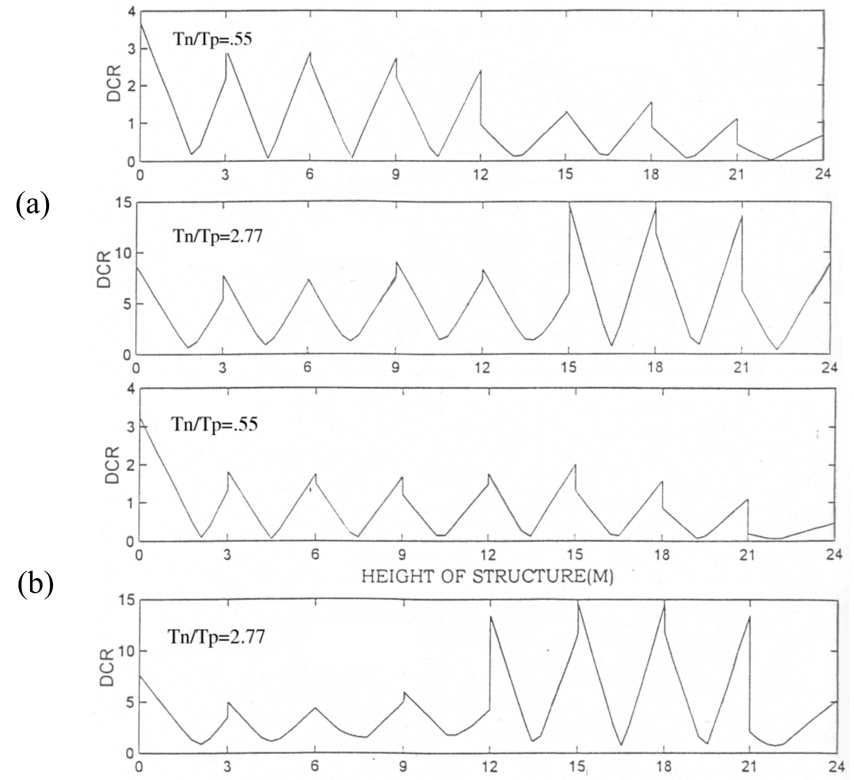

Figure 3. Distribution of maximum bending DCR. (a) Interior columns; (b) Exterior columns

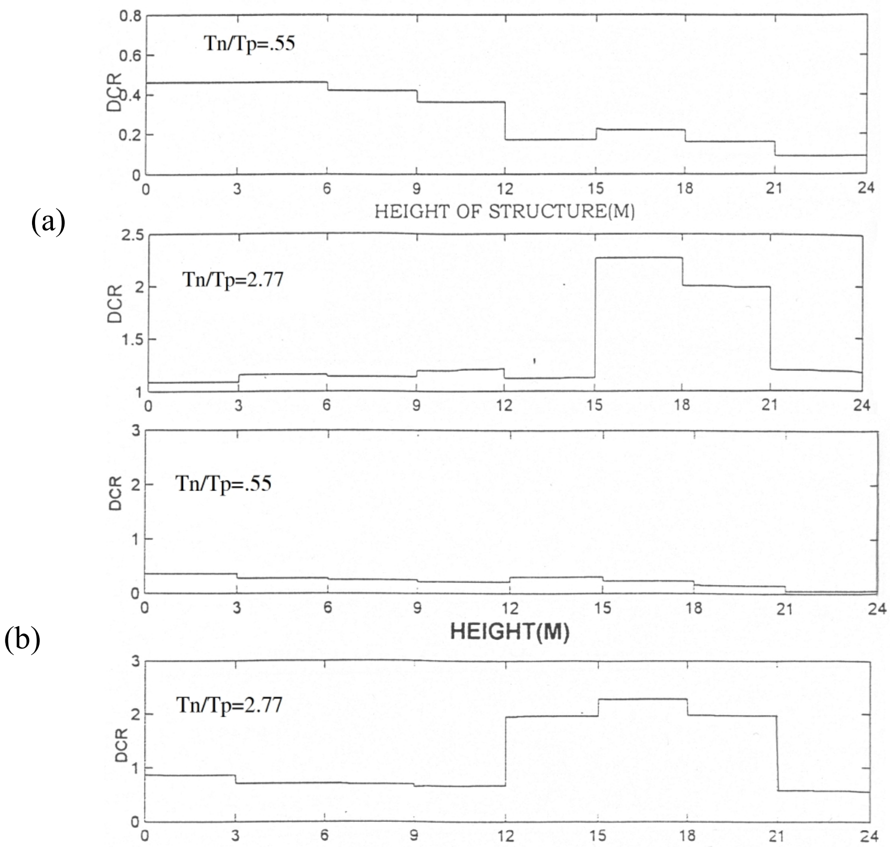

Figure 4. Distribution of maximum shear DCR. (a) Interior columns; (b) Exterior columns

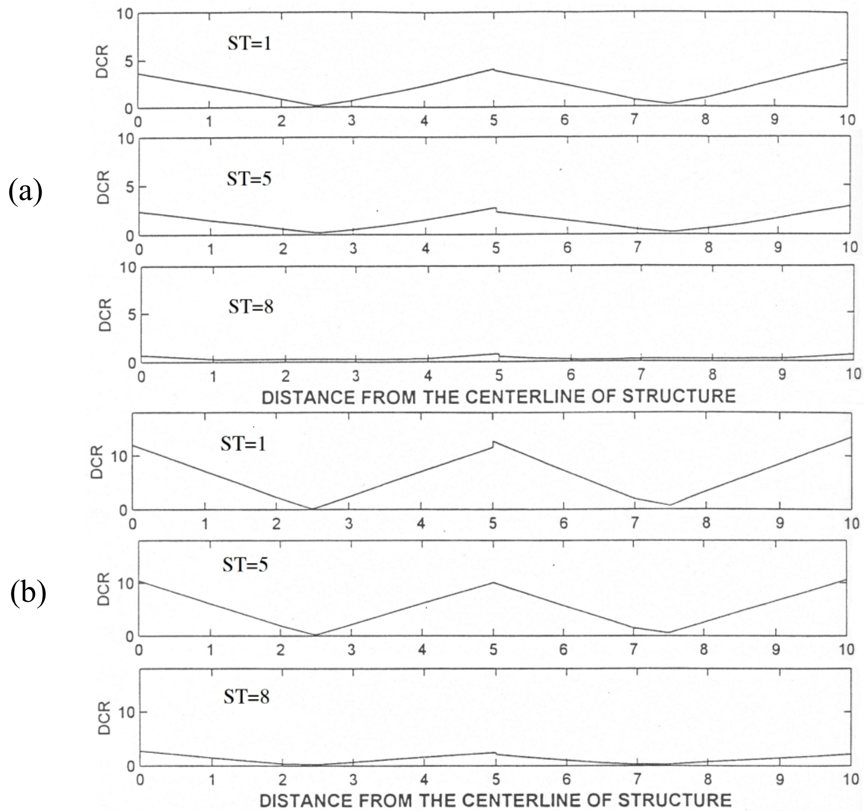

Figure 5. Maximum bending DCR in beams. (a) T_n/T_p =0.55; (b) T_n/T_p =2.77

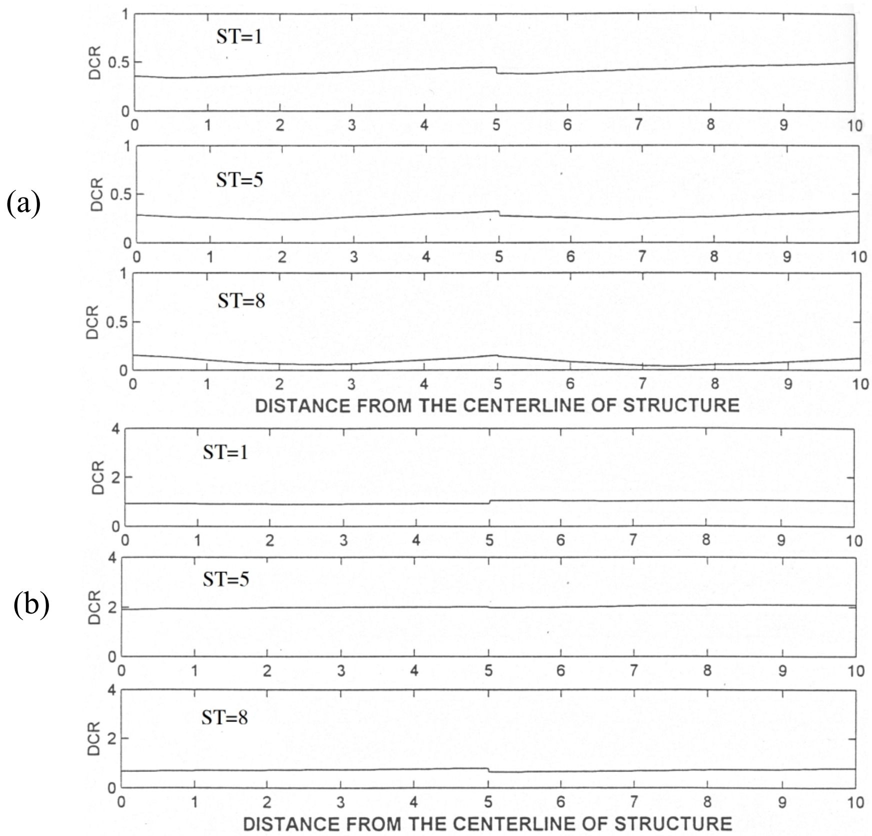

Figure 6. Maximum shear DCR in beams. (a) T_n/T_p =0.55; (b) T_n/T_p =2.77

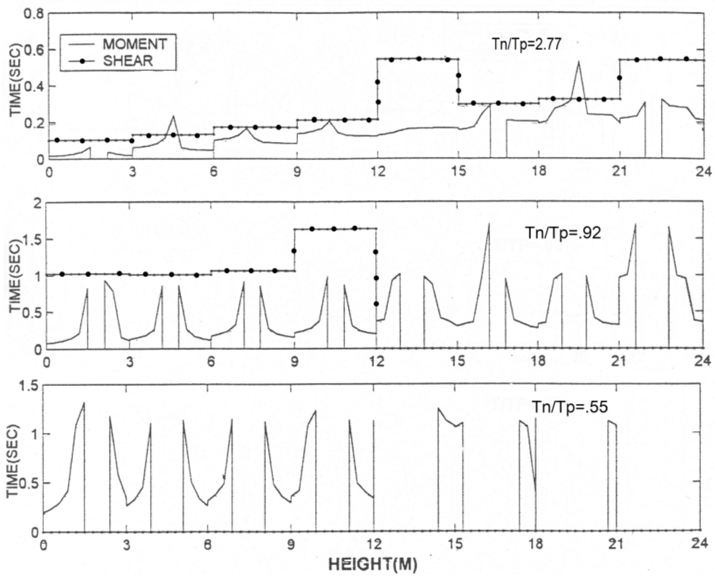

Figure 7. Times of shear and flexural DCR's first unit value in the interior column

3.3. Evaluating the sequence of shear and flexural DCR's attaining their maxima

In order to evaluate the effects of T_n/T_p on the pattern of hinge formation in the structure and the fact that initiation of hinges would be in the form of flexural or shear hinges, in this section, the times that shear and flexural DCR's first reach the unit value is calculated. The results for the interior column of the 8-story structure for three different values of T_n/T_p are shown in Figure 7.

It can be seen that as T_n/T_p increases, a larger number of shear and flexural hinges are formed in the columns and also the time lag for shear hinges forming after flexural hinges decreases, and even in some cases shear hinges form first. All these facts imply that the structural members' behavior becomes closer to a shear behavior under this type of waves.

3.4. Evaluating the time precedence of flexural and shear DCR's along the beams

For a purpose similar to the previous section, variation of the time that the shear and flexural DCR's achieve unit value for different ratios of T_n/T_p is calculated. Figure 8 shows the results for the stories 1, 5 and 8 of the 8-story structure for two different values of T_n/T_p .

These figures show that as T_n/T_p increases, the possibility of shear hinge forming increases. Although most of hinges formed are flexural, but as T_n/T_p increases, the time of shear and flexural DCR's becoming unity is closer to each other. This point again shows that the structural members' behavior tends to a shear behavior.

3.5. Evaluating the variation of area under column's shear and flexural DCR's

The distribution of maximum shear and flexural DCR's along the height of structure constitutes a continuous curve. The area under each of these curves is a measure of the total demands on the structure due to all stories. Thus, in this part, values of the areas under shear and flexural DCR's along structure's height for each value of T_n/T_p are calculated. The results of the 8-story structure are shown for the interior and exterior columns in Figure 9. It can be observed that as the T_n/T_p ratio increases, the areas under these curves also increase.

This shows a growth in force demands on the structure for larger values of T_n/T_p .

(a)

(b)

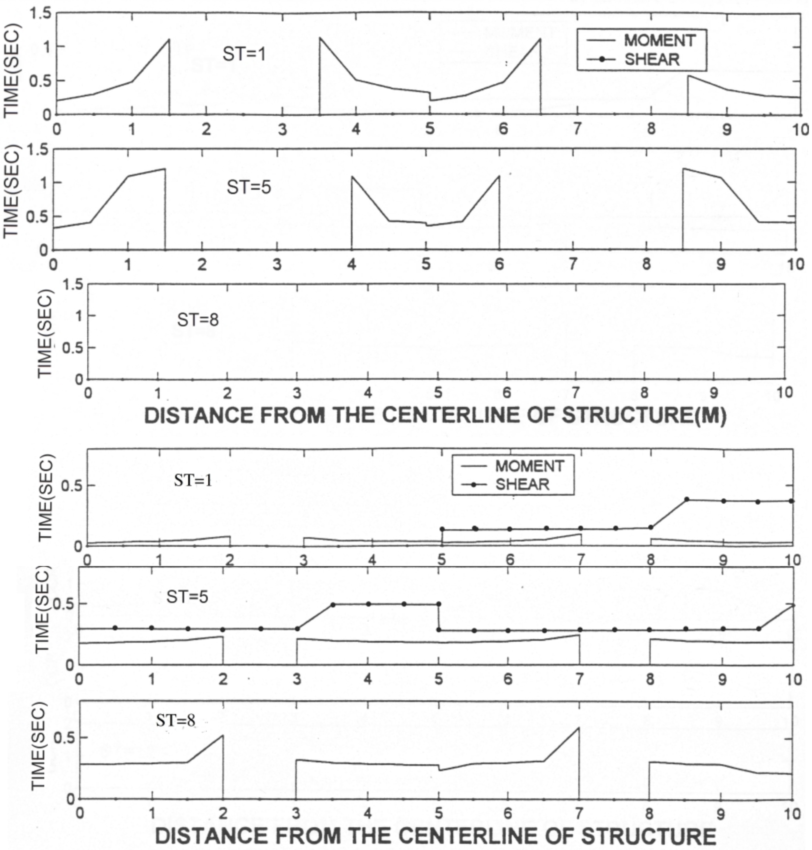

Figure 8. Variation of the time that the shear and flexural DCR's achieve unit value in beams. (a) T_n/T_p =0.55; (b) T_n/T_p =2.77

Area

(a)

Area

(b)

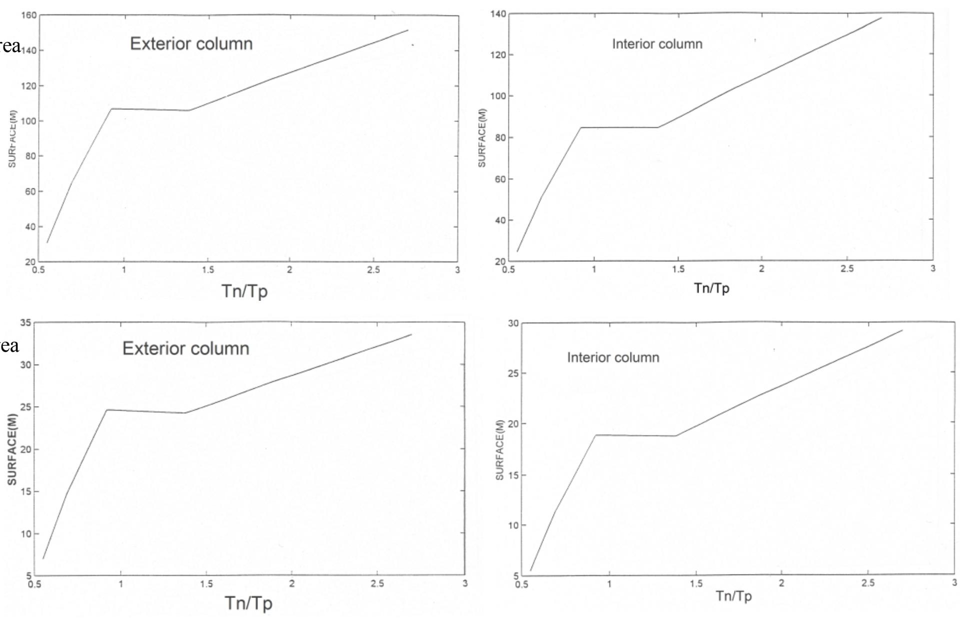

Figure 9. The areas under the whole DCR curves along the structure's height versus T_n/T_p .

(a) Moment; (b) Shear

3.6. Evaluating the variation of the centroid of the area under shear and flexural DCR curves for columns

As mentioned in Section 3.5, the areas under shear and flexural DCR curves are proportional to the total demand on the structure. In this regard, the center of this area can also be considered as the center of accumulation of structural demand or damage. In this section, variation of this center of structural damage with T_n/T_p is depicted. The results for the interior and exterior columns of the 8-story structure are shown in Figure 10. It can be clearly seen that as T_n/T_p increases, the centroid of the structural damage tends to shift to upper stories of the structure. This can be on account of the effect of higher modes due to propagation of waves.

3.7. Evaluating the adequacy of the fundamental mode to characterize the total response

In the code-based procedures, approaches based on the first dominant mode are usually used for determining the response of the structure subjected to a lateral load. Hence, in this section, the main objective is to evaluate the adequacy of the first vibrational mode for calculating the total response of the structure. In this regard, the maximum shear and flexural DCR's calculated using only the first mode of the structure are compared with those of using all of the participating vibrational modes. For this comparison, the values using the contribution of all modes are normalized to those of using only the first mode. Results are shown in Figure 11.

It can be seen that using only the first mode for determining the final response of the structure has more noticeable errors in this case. This error is more highlighted in the upper stories.

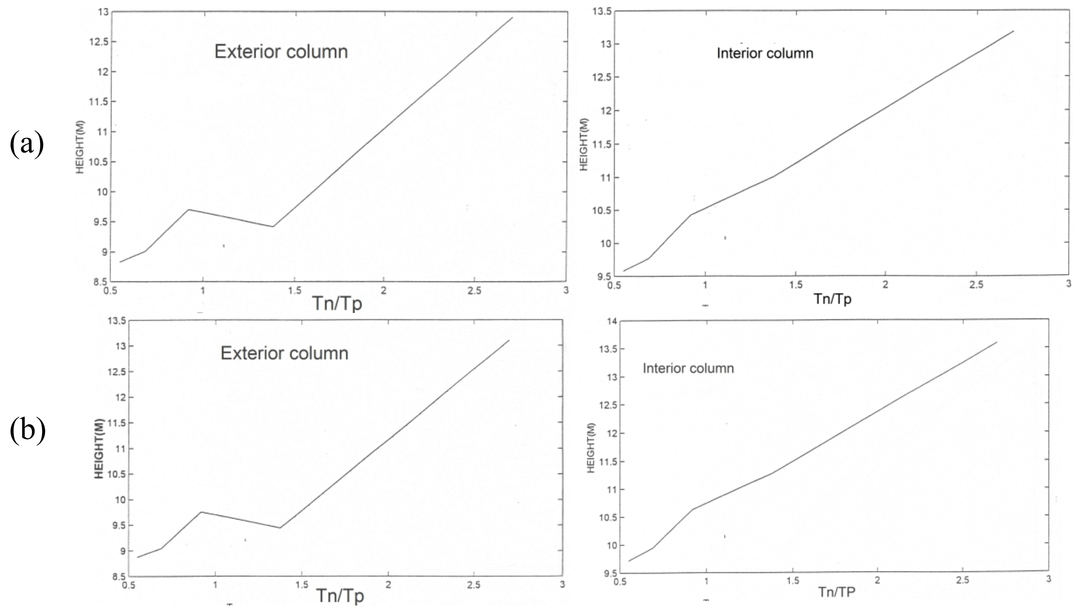

Figure 10. Position of the center of structural demand; interior and exterior columns.
(a) Moment; (b) Shear

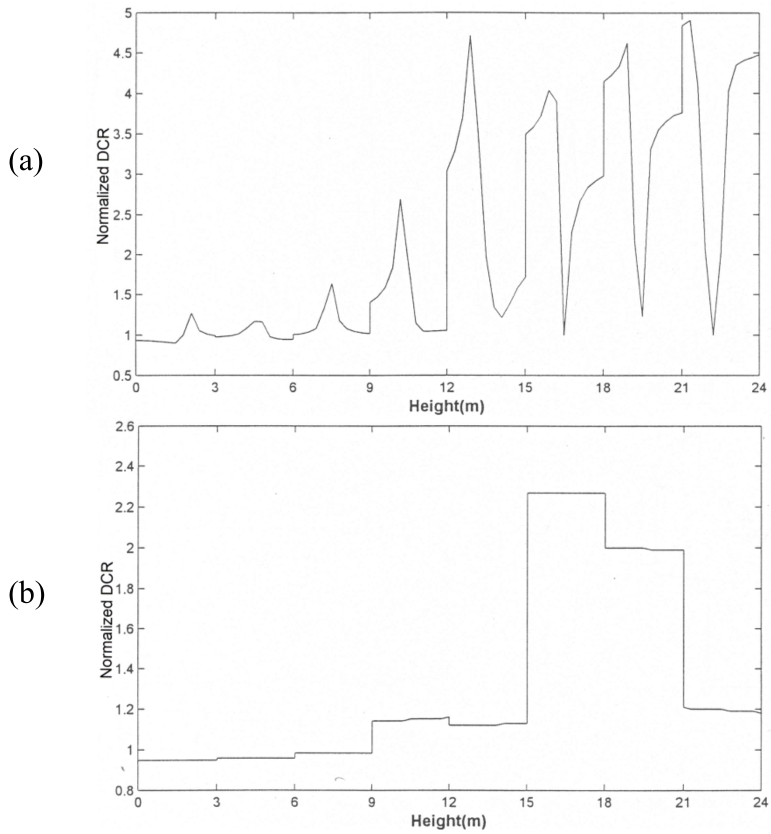

Figure 11. DCR values using all of the vibrational modes normalized to those using only the first mode; interior column; T_n/T_p = 2.7. (a) Moment; (b) Shear

4. Analysis under the tabas near-field earthquake record

In this section, the structures under study are subjected to some near-field ground motion records. For brevity, only results of the 8-story structure are presented for the Tabas earthquake. Results for other cases are roughly similar for the purposes of this study. The Tabas record is shown in Figure 12. As observed, the Tabas record is a near-field earthquake and has a distinct pulse clearly seen in its velocity and displacement records. Interestingly similar to what is assumed for the cosine pulse in Figure 2, the peak ground velocity and displacement for the Tabas earthquake are about 1 m/s and 1 m, respectively. The half period of this pulse, equivalent to the period of a cosine pulse, appears in the figure to be about 2.5 sec, resulting in T_n/T_p = 0.4. Therefore, for the 8-story building, the response under Tabas earthquake is expected to be overwhelmed by the free vibration characteristics of the building.

4.1. Distribution of the maximum shear and flexural DCR's for the columns

The 8-story structure is subjected to Tabas ground motion record and the maximum shear and flexural DCR's along the columns are calculated. The maxima for the interior column are presented in Figure 13. As observed, the values of maximum shear and flexural DCR's in this case are very similar to those of the simple pulse with T_n/T_p =0.55. In this study the structure and the analysis are assumed to be linear, hence the results are obtained by neglecting the material nonlinearity effects. However, if the material nonlinearity is considered, the values of DCRs will decrease, but the general trend would be similar to the linear case. This fact can also be seen in Kalkan and Kunnath [13].

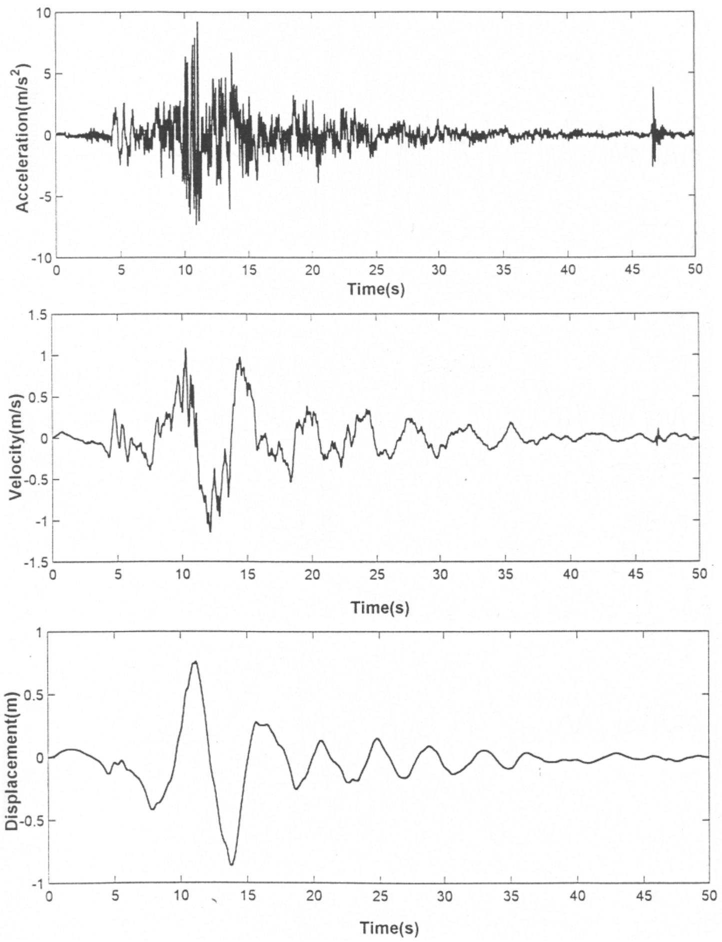

Figure 12. Time histories of the Tabas earthquake

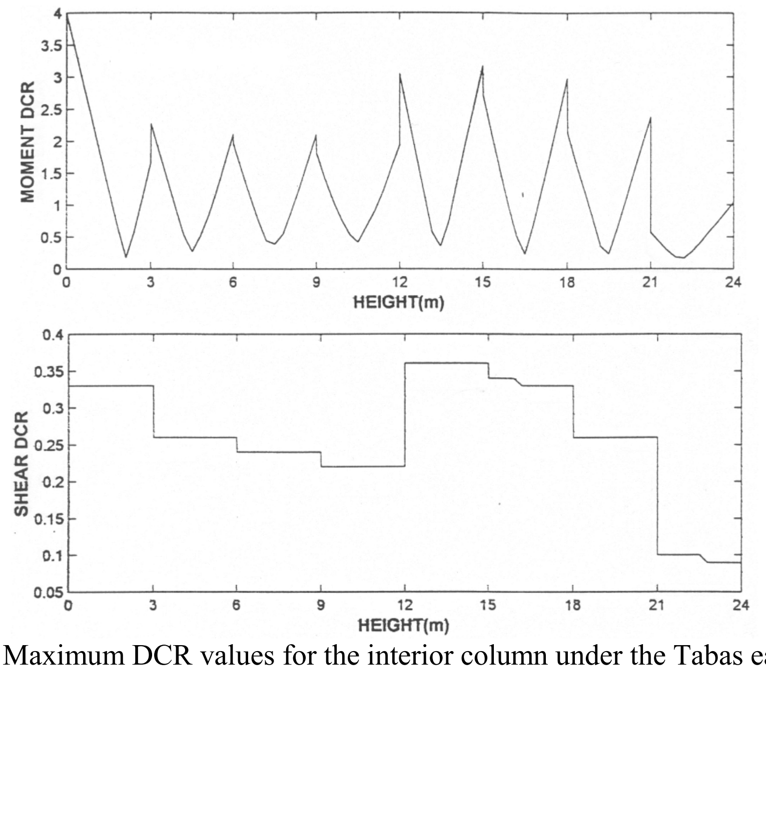

Figure 13. Maximum DCR values for the interior column under the Tabas earthquake.

4.2. Evaluating the time sequence of shear and flexural DCR's reaching unity in columns

In this section, the times that shear and flexural DCR's first surpass unity, i.e., the time thresholds that demand of a member exceed its capacity, are computed along columns. Figure 14 shows the results of this evaluation for the interior column of the 8-story structure under the Tabas earthquake. It can be observed that no shear hinge is formed in this case. All of the hinges are flexural. This can be due to the point that the T_n/T_p ratio is not large enough to make shear hinges form in the structure. This is quite similar to the results of Figure 7 under the simple pulse with a similar T_n/T_p .

4.3. Evaluating the times of shear and flexural DCR's reaching unity in beams

The times that shear and flexural DCR's achieve unit value along beams in the 8-story structure under the Tabas earthquake are also determined. The results of such a computation for the first and the last stories are shown in Figure 15. As is observed, again the formed hinges are flexural and this point shows that T_n/T_p is not large enough to make shear hinges along beams. This result is the same as what was concluded in Figure 8 under the simple pulse with a similar T_n/T_p .

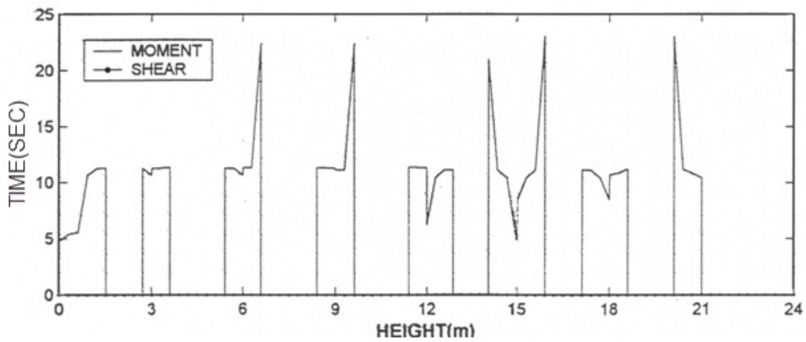

Figure 14. Times of the shear and flexural DCR's first unit value; interior column

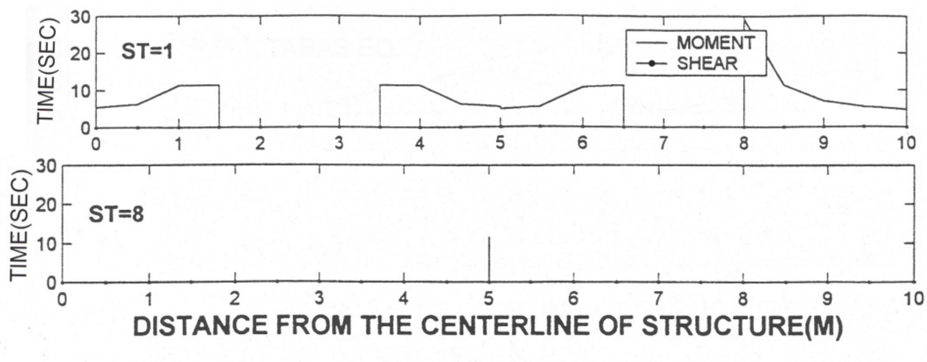

Figure 15. Times of the shear and flexural DCR's first unit value in the beams

5. Conclusions

In this paper, responses of a selected structure to a near-field pulse and earthquake were evaluated. Results show that the response is very sensitive to the ratio of natural period of the structure to the governing period of ground shaking pulse, T_n/T_p . As this ratio increases, the response makes a transition from pulse-dominated to free-vibration-dominated and the maximum shear and flexural DCR's increase noticeably in upper stories of the structure. In addition, as the ratio increases, the force demand increases and the centroid of the whole

DCR curve along structure's height, regarded as centroid of structural damage, shifts to upper stories. Inadequacy of using only the first mode to calculate the lateral response especially in upper stories and tending of the structural members behavior to a shear behavior are of other effects of a larger T_n/T_p. The propagation of waves in structure and contribution of higher modes can be responsible for such a behavior.

It was seen that the behavior of structure subjected to a near-field ground motion record and a simple pulse are very similar. All of the facts observed in the response of structure subjected to a simple pulse again were seen in the response to the actual record. This shows the appropriate accuracy of using a simple pulse for seismic behavior evaluation in place of the actual near-field ground motion record.

6. References

[1] US-Japan workshop proceeding on Mitigation of Earthquake Damage in Near-Field Urban Area, Hawaii, 1998.
[2] W. D. Iwan, Near-field consideration in specification of seismic design motion for structures, 10th European Conf. on Earthquake Eng. (1995) 257-267.
[3] W. D. Iwan, Drift spectrum measure of demand for earthquake ground motion, Journal of Structural Engineering, Apr. 1997.
[4] L. Decanini, F. Mouaioli, R. Saragoni, Energy and displacement demand imposed by near-source ground Motion, 12WCEE (2000), Paper No. 1136.
[5] P. K. Malhotra, Response of building to near-field pulse-like ground motion, Earthquake Engineering and Structural Dynamics, 28 (1999) 1309-1326.
[6] B. Alavi, H. Krawinkler, Consideration of near-fault ground motion effects in seismic design, 12WCEE (2000) paper No. 2665.
[7] D. Yang, J. Pan, G. Li, Interstory drift ratio of building structures subjected to near-fault-ground motions based on generalized drift spectral analysis, Soil Dynamics and Earthquake Engineering, 30 (2010) 1182-1197.
[8] V. Sharif, A study on the effects of near-field earthquakes on the dynamic behavior of structures, M.Sc. Seminar, International Institute of Earthquake Engineering and Seismology, Iran, 2001.
[9] Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard 2800-05), 3rd Edition, Building and Housing Research Center, 2005.
[10] The Iranian Code for Design and Practice of Steel Structures (10th Clause of the National Building Regulations), Ministry of Roads and Urban Planning, 2010.
[11] M. J. Jabbarzadeh, Assessing wave propagation phenomena in 2D structures using the dynamic stiffness matrix, M.Sc. Thesis, International Institute of Earthquake Engineering and Seismology, Iran, 2000.
[12] V. Sharif, Evaluation of the effects of near-field earthquakes on distribution of shear forces and bending moments in structures, M.Sc. Thesis, International Institute of Earthquake Engineering and Seismology, Iran, 2001.
[13] E. Kalkan, S. K. Kunnath, Effects of fling step and forward directivity on seismic response of buildings, Earthquake Spectra, 22(2) (2006) 367-390.