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Seismic behavior of reinforced concrete frame structures

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ABSTRACT: This paper summarizes the results of a study on the seismic behavior of reinforced concrete moment-resisting frame (RC/MRF) structures based on analysis of earthquake strong motion. It is shown that the period of RC/MRF structures lengthens considerably during the earthquake motion in a transient and non-linear manner. Fundamental period values are obtained by generating a time history of the building period from the evolutionary spectra of strong motion records. A data base of 18 RC/MRF structures shows that the relationship $T=(0.035\ h_n)^{3/4}$ constitutes a close approximation of the fundamental period of RC/MRF if the stiffness along the principal directions of the buildings are similar. The data also indicate that detailing requirements do not generally increase the stiffness of RC/MRF buildings, and that, for most buildings, the nonstructural components have a marginal effect on the building period beyond the initial motion.

1 INTRODUCTION

The extensive network of seismic instruments in California recorded some significant earthquakes in recent years, including the 1989 Loma Prieta earthquake, and provides an unprecedented opportunity to investigate building behavior under strong earthquake motion. This paper reports on a study of reinforced concrete moment-resisting frame (RC/MRF) structures based on analysis of a data base of instrument records. The study focuses on the understanding of the stiffness degradation and its relationship to the period of the building.

2 BACKGROUND

The approximate formula (Method A) given in the Uniform Building Code (UBC) for computing the building period for RC/MRF structures is provided by the following equation (ICBO, 1988 &SEAOC, 1990):

$$T=C_t(h_n)^{3/4} \qquad (1)$$

with C_t=0.030,and h_n is the height, in feet, above the base to the level n.

This approximate value also serves for limiting the upper bound period value obtained by a more elaborate dynamic analysis (Method B of the UBC).

Prior versions of the 1988 UBC prescribed the period T as one-tenth of the total number of stories (T=0.1N). The change to formula (1) was first recommended in ATC3-06 (ATC, 1982) suggesting C_t values of 0.025 and 0.035 for RC/MRF and steel MRF, respectively. The 0.025 value was based on period data from 14 high rise (more than 6 stories) buildings that registered strong motion from the 1971 San Fernando earthquake. Results from dynamic analysis of some of the buildings in that data base are reported in reports on the San Fernando earthquake (NOAA/EERI, 1973), and a thorough compilation of period values is found in Mulhern and Maley,1973

An earlier study (Bertero, Bendimerad, & Shah, 1988) reviewed the original data base and recommendations. The review indicated inconsistencies in the data base as well as in the methodology for compiling period values and correlating period to building height. The 1989 Loma Prieta Earthquake offered an opportunity to gather additional data and perform further investigation on the behavior of reinforced concrete frame structures. The results are summarized in this paper.

3 SEISMIC RESPONSE AND FUNDAMENTAL PERIOD

Strong motion records as well as experimental data show that the fundamental period of a RC/MRF structures increases significantly during an earthquake. The increase in period is due to the degradation of lateral stiffness. Variation of period with the accumulation of structural damage during simulated earthquake shaking of a 1/5 scale 7-story reinforced concrete bare structure indicates an increase of period of as much as 250% (Bertero, 1984). Compilation of data of 10 reinforced concrete frame buildings from the 1971 San Fernando earthquake show an average increase of more than 100% between the pre-earthquake ambient period and the period value obtained from the strong motion records with increases as high as 200% for buildings that experienced structural damage (Mulhern and Malley, 1973). Ambient period values measured in concrete structures just after completion of construction and following a moderate earthquake indicate an increase in period value of up to 50% (Del Valle and Prince, 1965).

The commentary to the Blue Book (SEAOC, 1990) acknowledges that the actual building period of RC/MRF structures during an earthquake may be significantly longer than the one obtained from formula (1). It justifies the proposed formula based on three arguments: 1) the need for conservatism in design, 2) the participation of the nonstructural components, and 3) additional stiffness in modern structures that may result from detailing for ductility. While the first argument is trivial, the latter two arguments are not fully substantiated, thus the need to further investigate them.

4 DETERMINING BUILDING PERIOD FROM STRONG MOTION RECORDS

4.1 Conventional methods

Building earthquake response is highly nonstationary. This nonstationarity is reflected on seismic records and makes it difficult to assign a single value for the building period. Generally, the period of vibration of a building can be approximated directly from the recorded horizontal accelerograms, preferably on the upper floors of the building, by counting the number of zero crossings and averaging it for the duration of the motion. A more elaborate method, is to consider a Fourier Amplitude spectrum plot, and to identify the fundamental period value as the period of highest energy (i.e. amplitude). Similar filtering techniques can also be used. However, the period value obtained in this manner could not be consistently correlated to represent a design value because they relate to different stages of stiffness degradation and also includes higher modes of vibrations, bi-directional correlation, and soil-structure interaction. Within the linear-elastic concept of building design, the period obtained from instrument records should represent the fundamental mode of vibration before any damage or yielding has occurred in the structural system.

4.2 Proposed methodology

A rational approach to compile building periods from instrument records is to recognize that the stiffness corresponds to the rate of change of the load-deformation relationship, and hence this rate of change also represents the building period variation during strong motion. This suggests the development of a time history of the building period. Considering a record representing the horizontal component of the motion of a building, the time variation of the different vibrational modes can be obtained by means of the evolutionary spectrum (or physical spectrum) of the record. This spectrum exhibits the energy content of the record on the frequency-time plan (Bendimerad and Gere,1984). Hence, the dominant frequency can be identified and its time variation readily traced. This trace represents the time history of the fundamental period. As an illustration of this method Figure 1 shows plots for the evolutionary spectra of the horizontal component from two RC/MRF buildings. The first plot clearly indicates that the motion in this particular building was dominated by the fundamental mode. On the other hand, the second plot shows that the dynamic behavior was dominated by a complex combination of modes. However, in both cases the dominant period can be obtained

LOMA PRIETA EARTHQUAKE
October 17, 1989

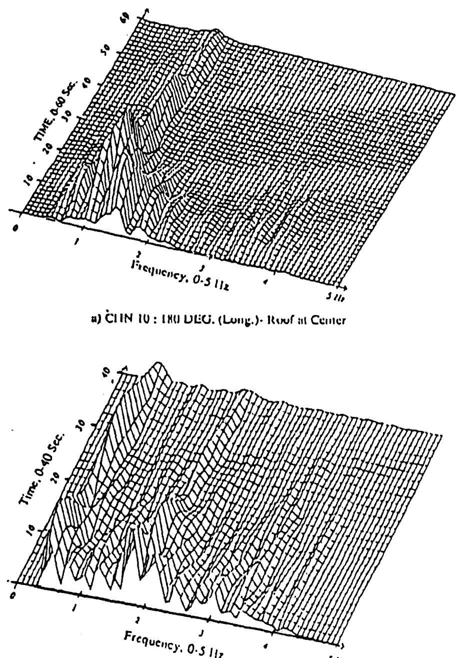


Figure 1. Time dependent spectra from two different records

Once the time history of the period is obtained, a single period value needs to be determined. This step can be developed from an understanding of the behavior of RC/MRF buildings that sustained extensive strong motion and experienced structural damage. In general one can identify four phases:

Phase 1: Low amplitude motion corresponding to the first few seconds of the record

Phase 2: Initial excursion phase. During this phase the high amplitude motion starts. There is an increase in period due essentially to the degradation of non structural elements. Structural damage has not initiated. The response of the building is essentially elastic.

Phase 3: High Amplitude response phase. This phase is identified by a rapid increase in period due to initial yielding of lateral load-resisting elements. There is no failure yet.

Phase 4: Final excursion phase. Corresponds to sustained high amplitude motion that could lead to failure.

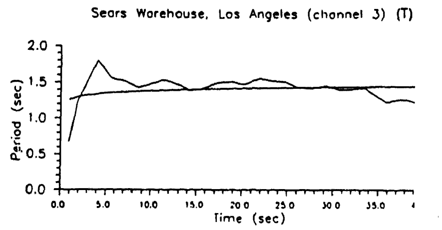
An illustration of this behavior is reproduced in Table 1 from a record of the 1971 San Fernando earthquake at the eight story Holiday Inn (Orion) Building. Structural damage on the building is reported as slight but nonstructural damage was extensive.

Table 1 Fundamental Period of the Holiday Inn (Orion) building (Longitudinal direction)

	Period (Sec)	Strong Motion Duration
Ambient	0.53	
Phase 1: Low Amplitude	0.50	t<3.0 sec
Phase 2: Initial Excursion	0.70	3.0 sec<t<11 sec
Phase 3: High Amplitude	1.20	t>11 sec
Post-Quake Period	0.72	

These phases can consistently be identified in RC/MRF structures. During the initial excursion phase (Phase 2), the response of the building is essentially elastic. A period value representative of this phase is beyond the highly transient part typical of the first few seconds of motion, but before any yielding or significant stiffness degradation occurs. Hence, this period constitutes an accurate approximation of the equivalent elastic period.

Unfortunately, a representative value of the initial excursion phase is difficult to identify directly from the time history of the building period because of its high non-linearity. This can be resolved by first smoothing the data to decrease the nonlinearity, and then fitting a logarithmic curve to the resulting set of points. The resulting smooth monolithic curve was found to be almost constant during this initial phase of motion, and hence, constitutes a good representation of the building's elastic response. This methodology was applied to several records obtained on RC/MRF buildings. A representative period value could readily be obtained from the logarithmic fit in each case. As an example, Figure 2 shows the smoothed time history and its corresponding logarithmic fit for horizontal strong motion components obtained at the Sears Warehouse building during the October 1, 1987 Whittier Earthquake. One can see that the building basically reacted elastically and remained within initial excursion phase. A representative elastic period of the building is obtained as T=1.3 sec in the transverse direction and T=1.4 sec in the longitudinal direction. The compilation from other buildings is reported in Bendimerad, Shah and Hoskins, 1991.



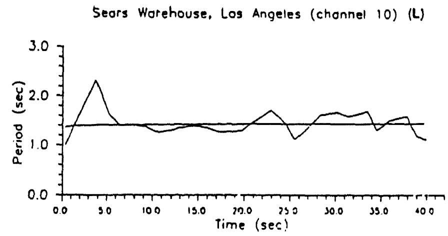


Figure 2. Time variation of building period with logarithmic fit.

Note that the proposed methodology inherently includes the participation of all elements that resist lateral loads wether specifically designed to be part of the lateral-load resisting system or not. However, the correlation of the period time histories with reported damages in the buildings, consistently indicates that in general the participation of the nonstructural components such as partitions and cladding is minimal compared to the stiffness of the structural elements and has practically little effect on the building period beyond the first five seconds of motion.

5 PERIOD VERSUS BUILDING HEIGHT

The methodology was used to compute the period values for a data base of 18 RC/MRF buildings that experienced strong motion in California (within the availability of digitized records). Reports on damage to the buildings were reviewed to further correlate the analytical period thus obtained with reported building behavior. The results are compiled in Table 2. A plot of building period versus building height is shown in Figure 3. One can see that a C_t value of 0.035 yields a good, and yet conservative correlation between fundamental period and total height of RC/MRF structures.

Table 2. RC/MRF structures and related period values

Bldg No.	Name and Location	Year Built	No. of Stories*	Height* (feet)	Period (sec) .03(h_n)$^{3/4}$	Trans.	Long.	Aver.
1	Holiday Inn Hollywood	1968	22/0	205/0	1.63	2.2	1.9	2.05
2	Holiday Inn Van Nuys	1966	7/0	66/0	0.70	1.2	1.4	1.3
3	Muir Medical Center Hollywood	1968	11/1	123/9	1.11	1.6	1.4	1.5
4	Sheraton Universal Los Angeles	1967	19/1	184/15	1.41	2.2	2.2	2.2
5	Holiday Inn Los Angeles	1965	7/0	66/0	0.70	0.9	1.2	1.05
6	Sears Warehouse Los Angeles	1970	5/1	119/20	1.08	1.3	1.4	1.35
7	First Federal Savings Pomona	1971	2/1	30/1	0.39	0.8	0.7	0.75
8	Bay Hill Office Cntr. San Bruno	1977	6/0	78/0	0.79	1.1	1.1	1.1
9	Pacific Park Plaza Emeryville	1981	30/0	300/0	2.16	2.8	2.8	2.8
10	Parking Structure I Stanford University	1987	4/0	48/0	0.55	0.7	1.1	0.9
11	Hilton Hotel Sherman Oaks	1968	13/0	124/0	1.12	1.4	1.3	1.35
12	Bank of California Los Angeles	1970	12/0	159/0	1.34	2.1	1.9	2.0
13	Tishman Airport Cntr Los Angeles	1967	14/1	160/15	1.35	1.6	1.8	1.7
14	Wilshire Coronado Los Angeles	1970	13/1	166/10	1.39	2.4	1.9	2.15
15	Brentwood Square Los Angeles	1966(?)	9/2	120/25	1.09	1.3	1.4	1.35
16	Hollywood Storage Bldg Hollywood	1925	14/0	149/9	1.28	2.3	0.8	1.55
17	Union Bank Bldg. Sherman Oaks	1964	13/2	188/21	1.52	2.3	1.9	2.1
18	IBM Building 012 San Jose	1968	5/0	65/0	0.69	0.83	0.83	0.83

* Above/Below Grade

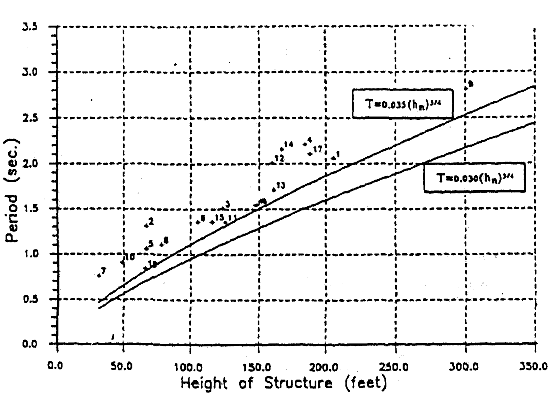


Figure 3. Period versus height for RC/MRF

Period for ductile (i.e. special) RC/MRF were collected separately to study the effects of ductility. Ten buildings in the data base were designed with special ductility provisions. The correlation of period to building height did not seem to indicate any increase in stiffness in those buildings compared to the remaining buildings in the data base.

6 EFFECT OF DIRECTIONAL RIGIDITY

The dynamic behavior of a building is to a great extent controlled by its rigidity. An earlier study by one of the authors on a 2 DOF uncoupled oscillator showed that the resultant deformational response of the structure not only depends on the frequencies (or periods) along the two principal directions, but also on the relative ratio between the frequencies. The soft direction of the response (i.e. the direction of longer period) tends to dominate the resultant response in both amplitude of deformation and direction (Safak & Bendimerad,1988). This behavior was recognized in those buildings in the data base that have significantly differing rigidities along their principal directions. An illustration is provided in Figure 4. The building time history plot clearly indicates a much longer period for the softer transverse direction compared to the more rigid longitudinal direction. The related strong motion displacement time histories and response spectra shows a similar relationship in the response. This indicates that in these buildings, the period obtained from the approximate formula may not result in a conservative design especially if the design is controlled by drift.

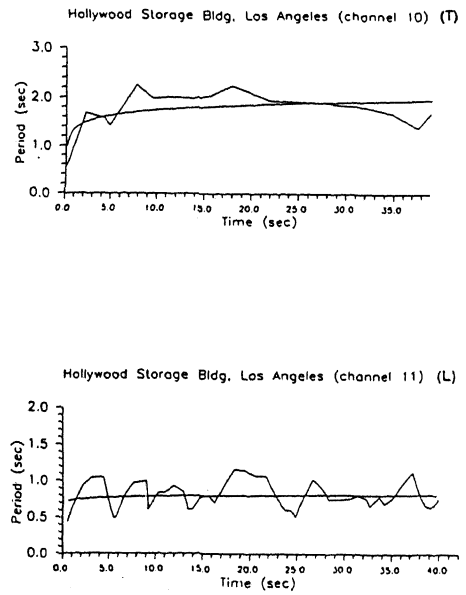


Figure 4. Illustration of response for buildings with different rigidities

7 CONCLUSIONS

The analysis of ground motion records from reinforced concrete moment-resisting frame structures indicates that their response is highly nonstationary but could be characterized by four phases related to increased motion: A low amplitude response for up to 5 seconds of motion, an initial excursion phase in which the building is respond ing essentially elastically with increase amplitudes, a high amplitude response starting with the initiation of stiffness degradation and a significant increase in period (as much as 200% compared to ambient), and a final excursion phase of sustained high amplitude motion. There is always a permanent loss of stiffness resulting in higher post-earthquake ambient period compared to pre-earthquake ambient period.

The significant lengthening of building period seems typical for RC/MRF structures. Hence, a building response does not exhibit a single fundamental period value that could be considered for design. This study suggests that, for the purpose of pseudo-elastic analysis, a reliable value for building period could be obtained by considering the period value representative of the initial excursion phase. A methodology for obtaining such a value is proposed and consists of developing a smoothed time history of the building period from the evolutionary spectra of strong motion records and fitting a logarithmic curve. The initial excursion phase is fairly well represented in this fit and an average elastic period could be obtained to represent the fundamental period of the building along each of the principal directions. A data of 18 RC/MRF buildings show that a relationship based on $T=(0.035\ h_n)^{3/4}$ constitutes a close approximation of the elastic fundamental period of RC/MRF buildings if the stiffness along the principal directions of the buildings are similar. The data also indicate that drift control and other detailing requirements do not generally increase the stiffness of RC/MRF buildings, and that for most buildings the nonstructural components such as cladding and partitions have no effects on the building period beyond the first five seconds of motion. Finally, the pseudo-elastic design procedure could be greatly improved by incorporating the relative rigidity between the principal directions of the building into the approximate formula for computing the period.

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