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# EFFECTIVE VISCOUS DAMPING IN REINFORCED CONCRETE BUILDINGS: ESTIMATION BASED ON MEASURED STRONG MOTION RESPONSE

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#### Abstract

Use of constant damping ratio, often at 2% or 5% level of critical damping, is common in the design and analysis of reinforced concrete buildings. Using an empirical method that extracts both the capacity curve and the effective viscous damping from actual strong motion response data recorded in buildings, we show that the effective viscous damping ratio in low to mid-rise RC buildings responding at their dominant mode (equivalent of fundamental mode in linear systems) varies linearly with the inverse of the effective period. We demonstrate the method using acceleration records obtained in an actual 7-story RC building intensely shaken and damaged during earthquakes. The consequences of the observed variation of damping ratio versus the constant damping ratio that is assumed in the current practice of RC building design are discussed and illustrated using the 7-story RC building as a testbed.

Keywords: effective viscous damping; reinforced concrete buildings; energy dissipation; inelastic response



### 1. Introduction

An approach proposed by Dowgala [1] to extract mass-normalized restoring and damping forces from acceleration response records is used to study nature of effective viscous damping in reinforced concrete buildings. The method makes no assumption regarding the nature of the response, i.e. whether the response is linear or nonlinear elastic, or inelastic. Below the method is briefly explained and illustrated using the acceleration response of an actual 7-story reinforced concrete building recorded during strong earthquakes. The focus of this study is on the nature of effective viscous damping and the corresponding damping ratio.

## 2. Methodology

Assuming velocity proportional viscous damping, the equation of motion for a single degree of freedom (SDOF) structure subjected to base acceleration can be written as

$$M[\ddot{x}(t) + \ddot{x}_g(t)] + C\dot{x}(t) + Fs(t) = 0$$
(1)

where,

М	:	mass of the structure
С	:	effective viscous damping coefficient of the structure
Fs(t)	:	restoring force provided by the structural system; if the structure remains
		linear-elastic, $Fs(t) = Kx(t)$ with K being the stiffness of the structure
x(t)	:	displacement relative to ground
$\dot{x}(t)$	:	velocity relative to ground
$\ddot{x}(t)$	:	acceleration relative to ground
$\ddot{x}_{q}(t)$	:	ground acceleration

Taking a mass-normalized formulation approach, the acceleration measured in the structure becomes the massnormalized inertial force. Then, the mass-normalized damping force can be written as:

$$C_m \dot{x}(t) = -\left[\ddot{x}(t) + \ddot{x}_g(t)\right] - F_{sm}(t)$$
<sup>(2)</sup>

where,

$C_m$ :	mass-normalized effective viscous damping coefficient
$C_m \dot{x}(t)$ :	mass-normalized viscous damping force
$\ddot{x}(t) + \ddot{x}_g(t)$ :	mass-normalized inertial force
$F_{sm}(t)$ :	mass-normalized restoring force

The procedure proposed by Dowgala [1] is used to estimate the mass-normalized damping coefficient. The procedure is based on the principle that peaks in restoring force should occur at instances of zero relative velocity which are also the instances of maximum distortion. If the velocity proportional damping force is present in the system, the inertial force peak will not coincide in time when the relative velocity is equal to zero. The difference in time between the zero-crossing in relative velocity and the peak in inertial force is used to estimate damping. Enforcing this principle yields a mass-normalized damping coefficient at each zero relative velocity instance for each inertial force peak. After fitting a log-normal distribution to the extracted values, one can obtain a single effective damping coefficient for the duration of the ground motion. The velocity proportional effective viscous damping ratio is written in terms of the mass-normalized damping coefficient and the natural period of a sub-critically structure as

$$\beta = \frac{C_m}{4\pi} T_n \tag{2-3}$$



wher	e,	
β	:	effective viscous damping ratio of the SDOF structure
$C_m$	:	mass-normalized effective viscous damping coefficient
$T_n$	:	natural period of the structure (apparent period of the dominant mode of response obtained from Fourier spectral response)

The proposed method can also be used to estimate the damping ratios of multiple degrees of freedom (MDOF) structures in which the first mode is the dominant mode of response by filtering out the second and higher modes from the records. The method has been applied to twenty-three laboratory RC specimens by Hesam, et al. [2, 3] and the details are given in [4]. It is observed that the mass-normalized damping coefficient remains nearly constant in the small-scale test specimens. Below, the method is applied to study an actual building that has experienced multiple damaging earthquakes.

## **3.** Description of the Building

The building is a 7-story RC hotel located in Van Nuys, California. In plan, it is 19.1 m by 45.7 m, along the north-south (transverse) and east-west (longitudinal) directions, respectively. The 20-meter tall building was designed in 1965 based on the Los Angeles City Building Code, and built in 1966 [5]. The structure is a rare building that was instrumented with accelerometers and subsequently damaged by earthquakes during which the accelerometers recorded the response of the structure. There are strong motion response records from fifteen earthquakes recorded over a period of forty years (between 1971 San Fernando and 2011 Newhall earthquakes). Table 1 shows the earthquakes during which accelerometers installed in the Van Nuys building recorded its response.

No.	Earthquake	Date of earthquake	Earthquake magnitude	Distance to epicenter [km]	
1	San Fernando	09/02/1971	6.6	22	
2	Whittier Narrows	01/10/1987	5.9	41	
3	Whittier Narrows aft.	04/10/1987	5.3	38	
4	Pasadena	03/10/1988	4.9	32	
5	Montebello	12/06/1989	4.1	34	
6	Malibu	19/01/1989	5.0	36	
7	Sierra Madre	28/06/1991	5.8	44	
8	Landers	28/06/1992	7.5	186	
9	Big Bear	28/06/1992	6.5	149	
10	Northridge	17/01/1994	6.5	1.5	
11	Northridge aft.	20/03/1994	5.2	1.2	
12	Northridge aft.	06/10/1994	4.5	10.8	
13	Chino Hills	07/29/2008	5.5	14.6	
14	Borrego Springs	07/07/2010	5.4	14	
15	Newhall	09/01/2011	4.2	7.3	

Table1 – Earthquakes for which response records from the 7-story RC hotel building in Van Nuys, California are available [4]

Two of these earthquakes caused visible damage to the structure. The building experienced minor damage mostly in its architectural elements during the 1971 San Fernando earthquake [6]. Jennings [7] describes it in more detail that there was "extensive damage to the interior plaster walls, to the plumbing fixtures, etc., on the



second, third, and fourth floors. The upper three floors were not damaged severely. The structural frame received some cracks, indicating strains beyond the elastic limit; the cracks were repaired with epoxy cement." The building suffered heavy damage in many of its fourth story columns during the 1994 Northridge earthquake. Table 2 shows the peak ground acceleration (PGA) and peak ground velocity (PGV) of the 1971 San Fernando and 1994 Northridge earthquakes. These values have been estimated by analyzing the acceleration data at the base of the 7-story hotel building. Certainly, the ground shaking during the 1994 Northridge earthquake was a lot more intense than that the building experienced during the 1971 San Fernando earthquake.

	1971 San Fernando		1994 Northridge	
	E-W	N-S	E-W	N-S
Peak ground acceleration [g]	0.1	0.3	0.6	0.6
Peak ground velocity [cm/s]	22	21	71	80

	Table 2 –	PGA and	l PGV at	the base	e of the	7-story	RC hotel	in Van	Nuys, (	CA
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Acceleration data recorded along the north-south (transverse) and east-west (longitudinal) directions during the 1971 San Fernando and 1994 Northridge earthquakes were analyzed to estimate the effective viscous damping and restoring force characteristics (hysteretic behavior) of the building at its dominant mode during these events.

#### 4. Results

In the following, the process of analyzing the response along the north-south direction of the building during the 1994 Northridge earthquake is presented in detail. Results from application of the same process to the Northridge records in the east-west direction, as well as to records from the 1971 San Fernando earthquake are summarized at the end.

Figure 1 shows the Fourier spectral response of the acceleration measured at the roof level during 1994 Northridge earthquake as well as the band-pass filter applied to it. The frequency with the maximum Fourier amplitude represents the frequency of the dominant mode, i.e. first mode, of response. The inverse of the dominant frequency is called the "apparent period" of the structure by Cecen [8]. In this study, the apparent period is used to estimate the effective viscous damping of the structure.



Figure 1 – 7-story hotel (1994 Northridge GM) – North-South direction – Fast Fourier Transform



Figures 2 and 3 show the ground acceleration and the roof acceleration responses. Figure 4 shows the roof velocity response relative to ground. Figure 5 shows the roof displacement response relative to ground. Figure 6 shows the estimated mass-normalized damping ratio.



Figure 2 – 7-story hotel (1994 Northridge GM) – North-South direction – Ground acceleration



Figure 3 - 7-story hotel (1994 Northridge GM) - North-South direction - Roof acceleration



Figure 4 - 7-story hotel (1994 Northridge GM) - North-South direction - Roof velocity relative to ground



Figure 5 – 7-story hotel (1994 Northridge GM) – North-South direction – Roof displacement relative to ground



Figure 6 – 7-story hotel (1994 Northridge GM) – North-South direction – Mass-normalized damping coefficient. The log-normal mean as well as one standard-deviation range for the estimates are shown.

Figure 7 shows the spectral displacement versus spectral acceleration of the roof. The mass participation factor is assumed to be 130%. Figure 8 shows the spectral displacement versus spectral acceleration of the roof, regardless of the direction of motion. The color bars in Figures 7 and 8 indicate, in seconds, the time of the response from the start of the motion.



Figure 7 - 7-story hotel (1994 Northridge GM) - North-South direction - Hysteresis



Figure 8 – 7-story hotel (1994 Northridge GM) – North-South direction – Force-displacement curve (capacity curve) envelops local peak responses, shown in spectral acceleration-spectral displacement.

The same procedure described for the north-south direction of the Northridge earthquake is followed for the eastwest direction for same earthquake as well as the data obtained from the two perpendicular directions of the 1971 San Fernando earthquake. Table 3 summarizes the results obtained from the analyses. Results indicate that the mass-normalized damping ratio stayed nearly constant (within 10% difference) along longitudinal and transverse directions during the 1971 San Fernando and the 1994 Northridge earthquakes: 0.45 and 0.49 along the longitudinal direction and 0.47 and 0.44 along the transverse direction. These observations are in agreement with the observations obtained from the twenty-three laboratory RC specimens [4]. It is also observed that the period of the structure along the east-west direction elongated by 16% from the 1971 San Fernando to the 1994 Northridge earthquake (1.2 sec vs. 1.4 sec). However, the period of the structure along north-south (transverse)



direction increased by 43%. It is estimated that the effective viscous damping ratio increased from 4.4% to 5.5% and from 5.3% to 7.0% along the east-west and north-south directions, respectively, during the 1971 San Fernando and the 1994 Northridge earthquakes.

	1971 San Fernando		1994 Northridge	
	E-W	N-S	E-W	N-S
Mass-normalized damping coefficient [1/s]	0.45	0.47	0.49	0.44
Period [s]	1.2	1.4	1.4	2.0
Effective viscous damping ratio	4.4%	5.3%	5.5%	7.0%

Table 3 - Estimates for the 7-story RC hotel building in Van Nuys, CA

## 2. Conclusions

Studying dynamic response data from twenty-three laboratory RC specimens with different levels of capacity and from a 7-story RC building, we found that the effective viscous damping coefficient may be assumed to be nearly constant, independent of the damage state of the structure. The corollary is that the corresponding effective viscous damping ratio varies linearly with the effective period of the dominant mode of the structure. If this observation is shown to hold true for a wide range of RC building structural systems, dominant mode (fundamental mode) damping ratios can be estimated empirically, which in turn would allow estimating the internal (restoring) forces in components of RC structural systems with less uncertainty. The proper modeling of damping ratio, an important parameter in capturing energy dissipation in a structure, would allow the improved estimation of the seismic response of RC buildings. When more response data recorded in buildings during earthquakes with different shaking intensity become available, the process described herein could be used to analyze the response data. Then, it might become possible to propose effective viscous damping ratios for different building structural configurations and for response levels. Based on the observations made during the study of laboratory RC specimens, the use of 2% effective viscous damping ratio in the design of reinforcedconcrete buildings, under design-level ground motion, is deemed appropriate. Use of a viscous damping ratio higher than an appropriate value estimated empirically from response of similar structures is likely to result in underestimation of the displacement the structure would experience during earthquake ground motions.

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