SEISMIC POWER FOR EARTHQUAKE DESIGN

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SUMMARY

The concept of seismic power is introduced in this paper as the time derivative of the dissipated energy of structure. In order to understand the role play for the delivery of the energy ground motion with time the study is restricted only to the world data set of destructive accelerograms with destructiveness potential factor larger than 4.0 cm. sec. This data base of 69 accelerograms corresponds to the following earthquakes: El Centro 1940, Eureka 1954, Parkfield 1966, San Fernando 1971, Nicaragua 1972, Rumania 1977, Imperial Valley 1979, Irpinia 1980, Chile 1985, Mexico 1985, San Salvador 1986, Loma Prieta 1989, Landers 1992, Northridge 1994 and Kobe 1995.This data base shows than less of 20% of recorded accelerograms in the world correspond to damaging conditions. The seismic power concept is analyzed by studying the evolution of the response of nonlinear elastoplastic one of degree of freedom oscillators subjected to the demand of these 69 accelerograms. The results indicates that defined power is proportional to the power function of the accelerograms. Therefore ductility requirements mainly depend of the way that earthquake deliver their energy on time, which is proportional to the definition of seismic power. Ductility requirements do not depend of the total energy of the earthquake.

The time distribution of nonlinear incursions and Rayleigh wave arrivals are also studied.

Finally, it has been found that damage velocity defined as the ratio between the relative nonlinear displacement of the structure and the corresponding duration are related with the seismic power.

INTRODUCTION

In the last quarter of a century, the collapse of many structures designed by good engineers according to modern seismic code has been observed. This situation has introduced many questions about the achievement of actual seismic design methods. The use of the ductility as unique parameter to define the level of structural damage and from there develop nonlinear response spectra has shown to be limited and unsafe specially for impulsive near source ground motions [Decanini *et al*. [2000]].

On the other hand the observed good correlation between the destructiveness potential factor defined by Araya and Saragoni [1984] with the observed damage [Uang and Bertero [1988] and Decanini, Gavarini and Mollaioli [1993]] has driven many researchers to study and develop seismic design methods based on energy concept [Bertero [1989]].

The development of seismic design methods based on energy concept is considered today to be one of the correct direction to eliminate some the above mentioned faults of actual code recommendations.

The results of recent studies for impulsive near source ground motions [Iwan [1997], Decanini *et al*. [2000]] as well as Saragoni and Gomez [1998] and Saragoni *et al.* [1998] for Rayleigh wave arrival of vibratory ground motion shown the importance of the delivery of the energy ground motion with time.

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In this paper a step forward is introduced by defining the concept of seismic power as the time derivative of the dissipated energy of structure.
However in order to understand the role play for the delivery of the energy ground motion with time the study must be restricted only to the world data set of destructive accelerograms i.e. accelerograms recorded at site where real damage was observed.
This restriction is imposed in order to study the damaging effect of the real arrival of seismic waves for demanding accelerograms.
The usual mixture of damaging with non damaging accelerograms to study nonlinear behavior usually drive to misleading conclusions since for damaging records the earthquake mechanism play a more significant role and their number is less than non damaging one.

DEFINITION OF A WORLD DATA BASE OF DESTRUCTIVE ACCELEROGRAMS.

Araya and Saragoni [1984] defined the destructiveness potential factor to allow to separate among accelerograms that produce real damage from the ones that are only ground vibration without produce damage to structures at the site of recording.

The destructiveness potential factor P_D of an accelerogram was defined as

$$P_D = \frac{\pi}{2g} \frac{\int_0^{t_0} a(t)dt}{\upsilon_0^2} \qquad (1)$$

Where

a (t) : accelerogram
ν_0 : intensity of zero crossings
g : acceleration of gravity

The correlation between P_{DH} and modified Mercalli intensity I is given by Saragoni, Sáez and Holmberg [1989] including the important data base of records of the 1985 Chile earthquake.

$$I = 4.56 + 1.50 \log P_{DH} \qquad (2)$$

Where P_{DH} is the sum of the P_D corresponding to the two horizontal records obtained at one accelerographic station.
By defining the threshold of damage at I = VI - VII it is obtained from Eq. (2) that $P_{DH} \geq 4.2$ cm. sec, therefore P_D for each component must be equal or larger than 2.0 cm.sec.
Decanini et al. [1993] and Mollaioli [1996] have studied 296 accelerograms of 29 earthquakes of the world verifying the correlation between P_{DH} and the observed damage measured by the macroseismic intensity IMCS.
They obtained the following correlation equation:

$$\log PDH = 0.60\ IMCS - 0.005\ I^2MCS - 3.00 \qquad (3)$$

which is similar to Eq. (2)
In order to define a world data base of destructive accelerograms, damaging accelerogram that satisfied that their P_D is larger than 4.0 cm.sec were chosen. These accelerograms corresponds to damage level at recording site larger than 7 in the Modified Mercalli intensity.
The data base was obtained from the study of more than 300 accelerograms of the world, remaining only 69 as destructive accelerograms. This date base corresponds to the following 15 earthquakes: El Centro 1940, Eureka 1954, Parkfield 1966, San Fernando 1971, Nicaragua 1972, Rumania 1977, Imperial Valley 1979, Irpinia 1980, Chile 1985, Mexico 1985, San Salvador 1986, Loma Prieta 1989, Landers 1992, Northridge 1994 and Kobe 1995.
In Table 1 the events are indicated in chronological order and the records with their corresponding P_D. Inspection of Table 1 shown that most of the destructive accelerograms (55) has been obtained in the last 15 years, with the only exception of Imperial Valley 1979.
The result of Table 1 shown than less of the 20% of recorded accelerogram in the world at ground level correspond to damaging conditions.

Table 1
World Data Base Of Destructive Accelerograms
P_d > 4.0 Cm.Sec.

Nº	EVENT	RECORD	PD cm.sec
1	El Centro 1940	NS	4.5
2	Eureka 1954	Eur79	11.6
3		Eur349	4.8
4	Parkfield 1966	Cho165	10.3
5	San Fernando 1971	Pac164	8.1
6		Pac254	6.2
7		Ori0	6.6
8		Ori270	5.2
9	Nicaragua 1972	Ess1	4.8
10	Rumania 1977	Bucar0	7.1
11	Imperial Valley 1979	Bonds230	24.9
12		Bonds140	7.3
13	Irpinia 1980	Calitwe	7.8
14		Calitns	5.9
15	Chile 1985	Llolleo N10ºE	19.8
16		Llolleo S80ºE	7.9
17		Viña del Mar S20ºW	11.6
18		Viña del Mar N70ºW	5.5
19		Llay llay N80ºW	10.1
20		Llay llay S10ºW	6.7
21		Ventanas EW	7.4
22		El Almendral N50ºE	4.6
23		El Almendral 540ºE	4.6
24		Melipilla NS	4.2
25	Mexico 1985	SCT Tran	129.5
26		TLHB Long	89.3
27		TLHB Tran	76.7
28		SCT Long	75.9
29		CDAF Tran	67.1
30		CDAF Long	35.8
31		TLHD Tran	20.8
32		TLHD Long	18.1
33	San Salvador 1986	Ign270	10.7
34		Ign180	5.1
35		Cig180	5.7
36		Uca180	4.9
37	Loma Prieta 1989	Holl0	17.0
38		Holl90	7.1
39		Capit0	12.7
40		Capit90	7.1
41		Foster90	11.2
43		Foster0	5.8
44		Corral0	8.4
45		Corral90	7.9
47		Ysidro0	4.5
48	Landers 1992	Jashua90	7.5
49		Jashua0	7.3
50	Northridge 1994	New360	20.9
51		New90	13.7
52		Syl360	8.6
53		Syl190	5.3
54		Smo90	4.7

Nº	EVENT	RECORD	PD cm.sec
55		Arl90	4.4
56	Kobe 1995	Jmakobns	20.0
57		Fksaew	19.9
58		Jmakobew	19.5
59		Fksans	18.4
60		Ekobns	15.4
61		Ekobew	14.9
62		Yaeans	13.7
63		Amskn30w	11.0
64		Mrgans	11.0
65		Amskn60e	7.7
66		Yaeaew	7.4
67		Tdoans	6.6
68		Mrgaew	4.4
69		Hikns	4.1

DEFINITION OF THE POWER FUNCTION OF ACCELEROGRAM

Saragoni and Hart [1974] defined the power function $P_a(t)$ of the accelerogram a(t) as

$$P_a(t) = a^2(t) \tag{4}$$

and the energy function:

$$W_a(t) = \int_0^t P_a(\tau)d\tau = \int_0^t a^2(\tau)d\tau \tag{5}$$

If must notice that the energy function defined by Saragoni and Hart do not correspond to the energy itself.

DEFINITION OF SEISMIC POWER

The seismic power $S_P(t)$ for a one degree of freedom nonlinear oscillator is defined as

$$S_P(t) = \frac{d}{dt}\left\{E_D^{'}(t)+E_H^{'}(t)\right\} \tag{6}$$

Where

$E_H^{'}(t)$: dissipated hysteric energy per unit mass

$E_D^{'}(t)$: dissipated energy by viscous dumping per unit mass

Studying the normalized dissipated energy for the 69 accelerograms of the world data set considered in this study for simple elastoplastic oscillators of natural periods 0.3. 0.7. 1.0. 1.5 and 2.0 secs and 5% of viscous dumping it was found that

$$E_D^{'}(t)+E_H^{'}(t) \propto W_a(t) \tag{7}$$

where $\propto$ denotes proportionality.

Figs. 1 shows the comparison between the normalized total dissipated energy with the normalized energy function for Kobe JMA NS and Chile Llolleo N10°E. It can be seen the coincidence between these empirical functions along all the normalized time.

This empirical result is similar for all the 69 analyzed accelerograms and support the result of Eq. (7) with the exception of a couple cases

This result is very important because it indicates that dissipated energy is delivered on time independent of the period of the oscillator at its function is proportional to the energy function of the demand of the earthquake motion.

Derivating Eq.(7) with respect to time it is obtained

$S_P(t) \propto P_a(t)$ (8)

This result indicates that defined seismic power is proportional to the power function of the accelerogram.
The flux of dissipated power by the structure is at the same rate of the flux of power of the earthquake. Therefore the velocity of damage of the structural is mainly controlled by the flux of the power function of the damaging accelerogram.
This result is the most important conclusion of this work, the damaging effect of earthquake is mainly due to the rate of delivery of earthquake energy with time, which can not be predicted by force or displacement nonlinear response spectra.

TIME DISTRIBUTION OF NONLINEAR INCURSIONS AND RAYLEIGH WAVE

Lobos and Saragoni [1997] have detected the presence of important Rayleigh waves in the accelerograms of the 1985 Chile earthquake. Fig.2 shows the arrival of 22 Rayleigh waves for the first 70 secs of the destructive accelerogram of Viña del Mar S20°W.
In this figure the arrival and duration of each Rayleigh wave are shown using bars. The width of each bar represents the duration Δt of the Rayleigh wave and the ordinate the average seismic power in the time interval Δt given by:

$$S_P(t_R) = \frac{\int_0^{t_R+\Delta t} a^2(t)dt - \int_0^{t_R} a^2(t)dt}{\Delta t} \quad (9)$$

Where t_R is the arrival time of the Rayleigh wave.
In Fig.2 are also shown two curves. The first one represent the energy function of the accelerogram. The second one the energy function only due to Rayleigh waves, which represents 70% of the energy function of this accelerogram.
The important increment of dissipated energy happen for each arrival of Rayleigh waves, which produce important increment in the slope of this curve. Larger values of the average seismic power of Rayleigh waves produce larger increment of dissipated energy.
These results show that seismogenetic characteristic of earthquake determine the way that elastoplastic simple oscillators dissipate the energy, since the structural damage is controlled by the presence of Rayleigh waves which depend of the characteristics of the source mechanism.
The results show that ductility requirements instead to be related with a large number of nonlinear incursions it is controlled by the way that earthquakes deliver their energy i.e. the seismic power. Therefore is difficult to predict nonlinear behavior using linear response spectra reduced or amplified by ductility factors [Saragoni [1990]]

DEFINITION OF DAMAGE VELOCITY

Damage velocity is defined as the ratio between the relative nonlinear displacements of the structure and their corresponding duration. Saragoni y Díaz [1992] calculated the damage velocity for simple ellastoplastic and stiffness degrading oscillators for a set of 28 accelerogram. It was found that the damage velocity are strongly correlated with the seismic power.
For impulsive earthquake such El Centro 1940, Tocachi Oki 1968, El Salvador 1986, Loma Prieta 1989, Northridge 1994 and Kobe 1995 the nonlinear incursion with the largest damage velocity value is significant different from the rest.
For vibratory earthquakes such the records of the 1985 Chile earthquake, characterize by long duration, the largest velocity of damage is obtained in a zone of similar values.
The damage velocity can be almost equal to the maximum ground velocity, values of the order of 70% of the maximum ground velocity are very common.
Maximum damage velocity between 1 to 3 km/hr are frequently observed. These velocities are in general greater than the one produced at laboratories. Therefore values of damage velocity turn laboratory test to be almost static and the interpretation of their results must be done under these restrictions.

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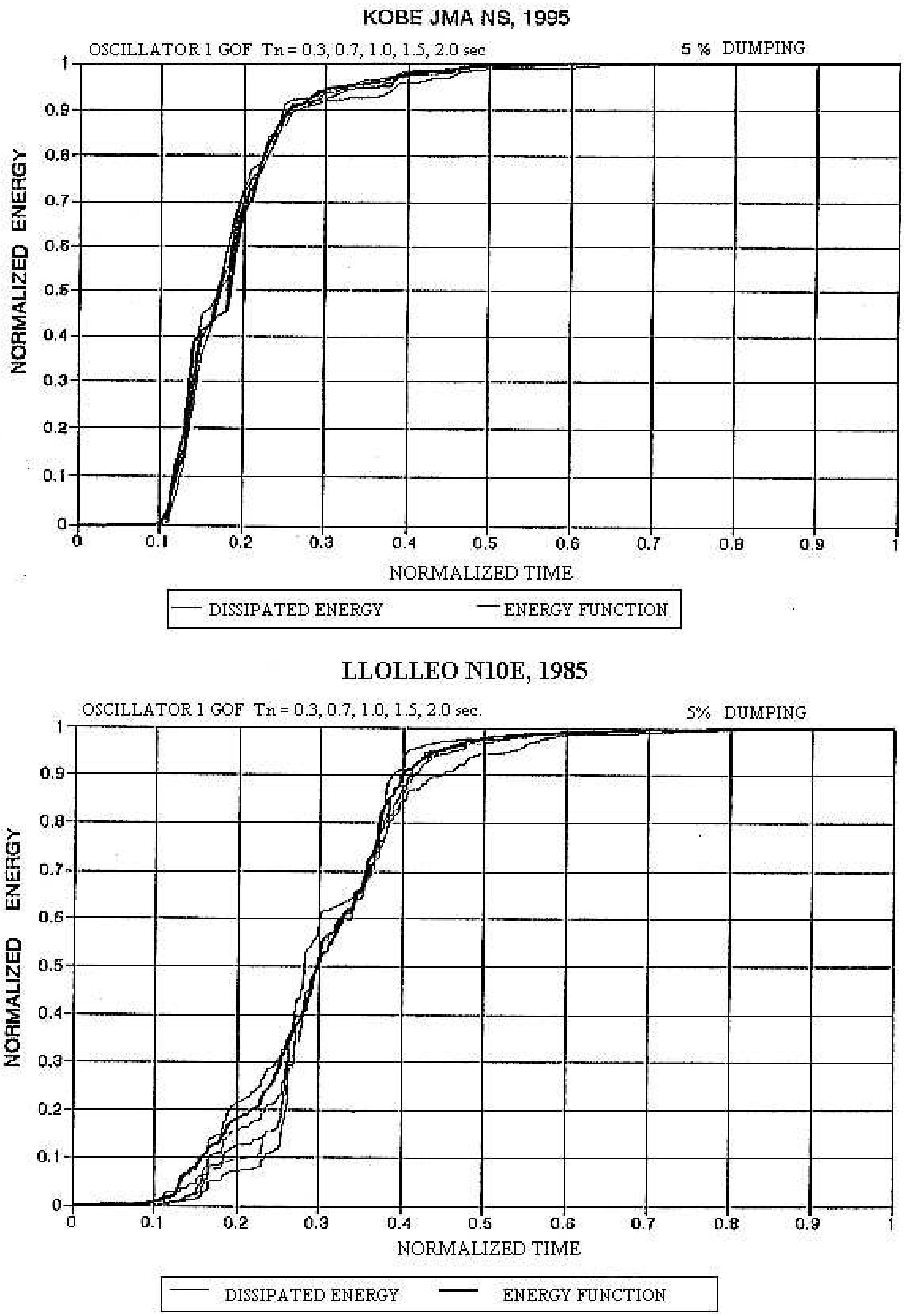

Fig. 1. Comparison Between Dissipated Energy and Accelerogram Demand Energy Function for Kobe JMA NS. 1995 and Llolleo N10ºE.1985

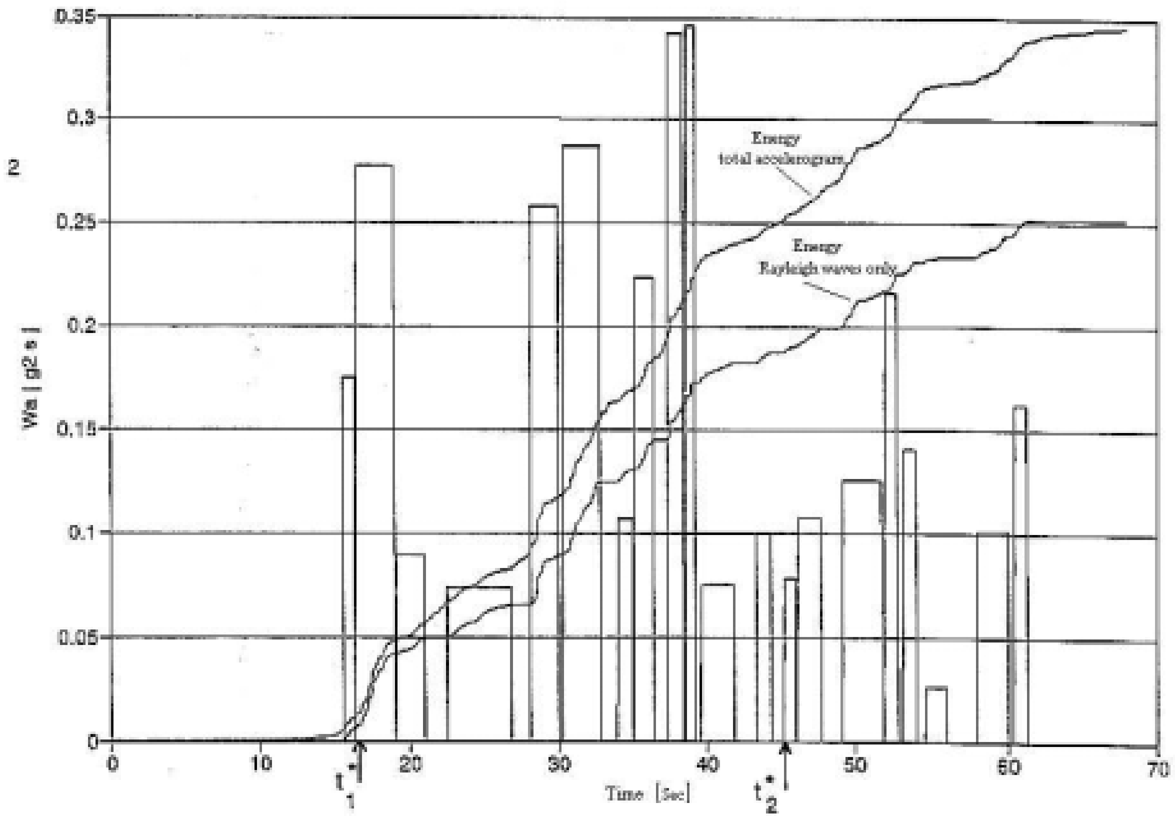

Fig. 2. Rayleigh Wave Effect on the Energy Function of the Accelerogram. Viña del Mar S20W.