XI International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XI
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

A NEW FORMULATION TO ASSESS THE SEISMIC DEMAND OF MASONRY STRUCTURES BY MEANS OF INPUT ENERGY

MEZA J. MIGUEL*, PEÑA FERNANDO†

* Instituto de Ingeniería (IdeI)
Universidad Nacional Autónoma de México
Circuito Escolar, s/n, Ciudad Universitaria, 04510 México D.F., México
Email: jmeza.mendez@gmail.com, www.iingen.unam.mx

† Instituto de Ingeniería (IdeI)
Universidad Nacional Autónoma de México
Circuito Escolar, s/n, Ciudad Universitaria, 04510 México D.F., México
Email: fpenam@iingen.unam.mx, www.iingen.unam.mx

Key words: Input Energy, Spectrum, Seismic demand, Unreinforced masonry.

Abstract. The main objective of this paper is to evaluate the elastic input energy of unreinforced masonry structures by means of the input energy spectrum. The energy is a novel approach which allows evaluating in a global and easily way the performance of the masonry structures. Structures modeled with non frame elements require of a great number of 2D or 3D elements, thereby making the calculation of the input energy a complicated issue. In this context, a new formulation that calculates the input energy using an input energy spectrum and the balance of energy is proposed. Two examples of application of unreinforced masonry structures were considered to evaluate the input energy and compare it with the proposed formula. The formula proposed shows interesting results that allowed identify the key features of the accelerograms that influence the input energy into structures.

1 INTRODUCTION

There are several methods proposed in the literature to quantify the severity, intensity or earthquake damage potential. Currently, all terms are intended to measure the same property of the ground motion: its effect on the structure. The only observed effect of ground motion on the structure is the permanent damage, so this measure is usually assessed by the degree of correlation with the observed damage. This can lead to a mistake, because the amount of damage depends on the qualities in building on the site. For this reason, macro-seismic scale of Modified Mercalli Intensity is not a reliable measurement of destructiveness potential (Orosco and Alfaro, 2008), though it is very used to describe the distribution of damage to the affected area. A rational correlation between a measure of intensity and observed structural damage could be established only if in the affected site buildings were uniformly designed in accordance with standard building code.

Unreinforced masonry buildings are structures with a particularly complex structural behavior. This complexity is given by the mechanical properties of the masonry, specially, by the low tensile strength of the material. Taking into account the uncertainties in the masonry, it is not easy to deal with a dynamic analysis by finite element programs, even with the current structural analysis programs. The masonry is one of the most complex materials to be represented numerically on an analytical model, due to the variability of behavior, type of material and workmanship. This characteristic of material, together with the unreinforced masonry structures are usually represented by a large number of elements, causes that a dynamic analysis utilizes high computing resources, taking several days, even weeks to be achieved (Lourenço, 2002).

Generally, most of the simplified analyses establish that the response of the structure can be calculated by considering the fundamental mode. The unreinforced masonry structures do not meet this requirement, because a single mode is not sufficient to determine an approximate response. To interpret the structure's response, two parameters are reviewed: displacement and base shear. However, the unreinforced masonry structures exhibit the phenomenon of softening, which excludes the base shear as a reliable indicator of the structural response. In the same way, the displacement has the problem that does not reflect the overall behavior of the structure, because every part of the structure may have different values. So, it is necessary to use other parameters. In this paper, the use of the energy as the main parameter to assess the potential damage of an earthquake is proposed.

Energy is a physical quantity that can be represented by a scalar, an appropriate quantity to synthesize the behavior of the structure. The main problem lies in figuring out how the input energy is distributed into the structure. At the end of an earthquake, all the input energy must have been dissipated by the structure through some dissipation mechanism. Some energy is absorbed by the structure through elastic dissipation mechanisms, such as viscous damping, and another part is absorbed by the mechanisms of inelastic energy dissipation, which is responsible of the structural damage. Therefore, the energy of a structure will be dissipated at the end of an earthquake in some kind of energy.

This paper addresses analysis of historic structures by using the concept of energy. Both, input energy and robust models (macroelements) for masonry structures, that are currently available, can be successfully used for the analysis of historic structures. For evaluating churches, it will be necessary evaluate each macroelement that it is composed of. In this paper just macroelement façades is analyzed. Façades of two typical churches from Mexico were selected. Input energy for different earthquakes will be shown and studied.

2 DESTRUCTIVINESS POTENTIAL OF EARTHQUAKES

This section is a review of proposed parameters for evaluating the potential damage of the earthquakes. Structural seismic analysis requires that the seismic action is properly defined for the purposes of obtaining reliable results. It is common to specify such a dynamic load using response spectra or acceleration histories, according to the selected method of analysis. Idealization of the action must reflect the characteristics of motions at the site of construction. Intensity measures discussed here are evaluated considering the peak acceleration, duration of strong motion and frequency content of earthquake ground motion.

2.1 Housner intensity

Housner (1952) proposed as a measure of the intensity the area under the pseudo-velocity spectrum in the range of 0.1 to 2.5s periods, for 5% damping ratio (Eq. 1).

$$I_H = \int_{0.1}^{2.5} S_v dT \tag{1}$$

Its biggest shortcoming is the inability to consider the effect of duration of strong motion. Spectral velocity is insensitive to the duration, while the energy entered to the structure increases monotonically with duration. On the other hand, the influence of the ratio v/a, or the duration of the pulse in case of impulsive excitation, is well represented by the velocity spectrum. The frequency content of the earthquake is implicitly represented by the spectral distribution of the pseudovelocity.

2.2 Arias intensity

Arias (1970) introduced the measure of the intensity of ground motion (Eq. 2) as:

$$I_A = \frac{\pi}{2g} \int_0^t a^2(t) dt \tag{2}$$

Where t is the duration of the registration of ground acceleration $a(t)$. Arias intensity (I_A) is closely connected with the root mean square acceleration and corresponds to the area below the total energy spectrum absorbed by the system of a single degree of freedom (SDF) at the end of the earthquake excitation. The I_A is not sensitive to frequency content and long acceleration pulses of the excitation. However, the accumulated energy of I_A brings out the impulsive character of the earthquake.

2.3 Araya destructive potential

Araya and Saragoni (1985) modified the Arias intensity to take into account the frequency content (Eq. 3). Defined the destructiveness potential (P_D) as:

$$P_D = \frac{I_A}{v_0^2} \tag{3}$$

In this expression, v_0 is the number of crossings per unit of time.

2.4 Energy dissipation Index

The parameters explained above depend only of earthquake characteristics and have implicit in the definition considerations of energy since they are directly related to the mean square acceleration. However, the structural response depends of the structural characteristics and the site where the structure is based. Therefore, damage potential indexes must considering explicitly the structural response. In view of this, Sucuoglu and Nurtug (1995) proposed an index of the destructiveness of an earthquake based on the energy dissipated by a system of one degree of freedom (Eq. 4), which is expressed as,

$$E_I = \frac{1}{T_{max}} \int_0^{Tmax} V_e dT \tag{4}$$

$$V_e = \sqrt{\frac{2E_d}{m}} \ ; \quad E_d = 2\xi m\omega_n \int_0^{y(t)} \dot{y} dy$$

Where E_I can be interpreted as the average energy dissipated by the spectral velocity of the system equivalent to SDF subject to earthquake motions. The energy dissipated by a simple oscillator during the seismic action is sensitive to the parameters that describe dynamic characteristics of the earthquake: effective duration, peak values and frequency content. However, damage potential index is sensitive to the v/a, to peak values, spectral content, but does not show a direct relationship to the duration of the earthquake.

2.5 Some remarks of these formulae

The input energy of family of linear SDF systems can be taken as a measure of potential earthquake damage. An attempt was make to consider the hysteretic energy dissipation to measure the intensity of the earthquake, but that is only true to quantify structural damage but not the damage potential of earthquake. The damage potential is the ability of the seismic excitation to cause damage, while the damage does depend heavily on structural characteristics. Seismic excitation with a given damage potential may cause different levels of damage on different systems, depending on the structural characteristics of the system. When using the input energy all the energies are included into, so that is the reason for proposes a formula to evaluate input energy. Additionally, the input energy combines the structural and earthquake characteristics.

3 NEW FORMULATION TO ASSESS THE EARTHQUAKE DEMAND

A new formulation is proposed to assess the damage seismic potential and to know the demand imposed on the structure. This equation expresses the balance of energy of the structure and allows us to interpret their earthquake demand from the concept of energy. The equation governing a SDF system subject to a horizontal seismic ground motion comes from the dynamic equilibrium equation, as shown in Equation 5.

$$mx(t) + cx(t) + kx(t) = -ma_g(t) \tag{5}$$

Where m is the mass; c the damping; k the stiffness of the system; $\ddot{x}(t)$, $\dot{x}(t)$, $x(t)$ are the acceleration, velocity and relative displacement, respectively; $a_g(t)$ is the ground acceleration. If equation 5 is multiplied by the differential increment of relative displacement dx (or $\dot{x}dt$) and integrating it throughout the duration of earthquake $(0, t)$, it is obtained a equation, which contains the integrated or cumulative vibration and represents the energy balance (Akiyama, 2003). The energy balance of SDF system for a given time t is,

$$\int_0^t m\ddot{x}\dot{x}dt + \int_0^t c\dot{x}^2dt + \int_0^t kx\dot{x}dt = \int_0^t -ma_g\dot{x}dt \tag{6}$$

$$W_k(t) + W_d(t) + W_s(t) = E(t)$$

Where E (input energy) is the work imposed by the dynamic forces at time t, W_{ek} the kinetic energy, W_{dd} the energy of dissipation by damping and, W_{es} the elastic strain energy. On the range of periods ranging from 0.2 to 5.0s, the relative input energy values are quite similar to the values of absolute input energy (Uang and Bertero, 1990). Therefore, it is no necessary for any differentiation between both energies. The input energy in the elastic range for a SDF can be calculated by adding the input energy contribution of each mode of vibration, for example for the mode 1, then,

$$\sum_{j=1}^{M}\{ \int_0^t m_{1j}\ddot{x}_{1j}\dot{x}_{1j}dt + \int_0^t 2m_{1j}\xi_j\omega_j\dot{x}_{1j}^2dt + \int_0^t m_{1j}\omega_j^2x_{1j}\dot{x}_{1j}dt \} = \sum_{j=1}^{M}\int_0^t m_{1j}a_g\dot{x}_{1j}dt \tag{7}$$

When the structure is composed of several degrees of freedom, by adding the energy of each node, the total energy of the system is obtained (Eq. 8).

$$\sum_{j=1}^{M}\{ \int_0^t m_{1j}\ddot{x}_{1j}\dot{x}_{1j}dt + \int_0^t 2m_{1j}\xi_j\omega_j\dot{x}_{1j}^2dt + \int_0^t m_{1j}\omega_j^2x_{1j}\dot{x}_{1j}dt \} = \sum_{j=1}^{M}\int_0^t m_{1j}a_g\dot{x}_{1j}dt$$

$$\sum_{j=1}^{M}\{ \int_0^t m_{2j}\ddot{x}_{2j}\dot{x}_{2j}dt + \int_0^t 2m_{2j}\xi_j\omega_j\dot{x}_{2j}^2dt + \int_0^t m_{2j}\omega_j^2x_{2j}\dot{x}_{2j}dt \} = \sum_{j=1}^{M}\int_0^t m_{2j}a_g\dot{x}_{1j}dt$$

$$\vdots$$

$$\sum_{j=1}^{M}\{ \int_0^t m_{Nj}\ddot{x}_{Nj}\dot{x}_{Nj}dt + \int_0^t 2m_{Nj}\xi_j\omega_j\dot{x}_{Nj}^2dt + \int_0^t m_{Nj}\omega_j^2x_{Nj}\dot{x}_{Nj}dt \} = \sum_{j=1}^{M}\int_0^t m_{Nj}a_g\dot{x}_{Nj}dt$$

$$E_{ti} = \sum_{j=1}^{M}\sum_{i=1}^{N}\left\{ \int_0^t m_{ij}\ddot{x}_{ij}\dot{x}_{ij}dt + \int_0^t 2m_{ij}\xi_j\omega_j\,\dot{x}_{ij}^2dt + \int_0^t m_{ij}\omega_j^2x_{ij}\dot{x}_{ij}dt \right\}$$
$$= \sum_{j=1}^{M}\sum_{i=1}^{N}\int_0^t m_{ij}a_g\dot{x}_{ij}dt \tag{8}$$

Where E_{ti} is the total input of energy multi-degree of freedom (MDF) system, ξ is the damping ratio or fraction of critical damping, and ω is the natural circular frequency of vibration. Substituting the modal expansion of the displacement ($\Gamma\phi q$), the velocity ($\Gamma\phi\dot{q}$) and the acceleration ($\Gamma\phi\ddot{q}$) of each mode, we have the following general equation to determine the input energy for a structure that behaves in the elastic range:

$$E_{ti} = \sum_{j=1}^{M}\sum_{i=1}^{N}\left\{ \int_0^t m_{ii}\Gamma_j^2\ddot{q}_j\dot{q}_j\phi_{ij}^2dt + \int_0^t 2m_{ii}\xi_j\omega_j\Gamma_j^2\dot{q}_j^2\phi_{ij}^2dt + \int_0^t m_{ii}\omega_j^2\Gamma_j^2q_j\dot{q}_j\phi_{ij}^2dt \right\} =$$
$$\sum_{j=1}^{M}\sum_{i=1}^{N}\int_0^t m_{ii}a_g\Gamma_j^2\dot{q}_j\phi_{ij}^2dt \tag{9}$$

Grouping common terms and using the orthogonality properties of natural modes,

$$E_{ti} = \sum_{j=1}^{M}\sum_{i=1}^{N} m_{ii}\phi_{ij}^2\Gamma_j^2\{ \int_0^t \ddot{q}_j\dot{q}_jdt + \int_0^t 2\xi_j\omega_j\dot{q}_j^2dt + \int_0^t \omega_j^2q_j\dot{q}_jdt \} =$$

$$= \sum_{j=1}^{M}\sum_{i=1}^{N} m_{ii}\phi_{ij}^2\Gamma_j^2\int_0^t a_g\dot{q}_jdt$$

$$\sum_{i=1}^{M}\sum_{i=1}^{N} m_{ii}\phi_{ij}^2 = 1$$

$$E_{ti} = \sum_{j=1}^{M}\Gamma_j^2\int_0^t a_g\dot{q}_jdt = \sum_{j=1}^{M}\Gamma_j^2E(T_j) \tag{10}$$

$$E_{ti}/M = \sum_{j=1}^{M}(\sum_{i=1}^{N}\phi_{ij})\Gamma_j\int_0^t a_g\dot{q}_jdt = \sum_{j=1}^{M}(\sum_{i=1}^{N}\phi_{ij})\Gamma_jE(T_j) \tag{11}$$

Where E_{ti}/M is the total input energy normalized respect to the mass of (MDF) system. ϕ_{ij} are the generalized modal coordinates of each node, Γ is the participation factor, and $E(T_j)$ is the spectral input energy of a SDF system for each period T_j. Equation 10 and 11 determine the elastic energy input from modal dynamic characteristics of the structure.

Should be noted that the equations 10 and 11 are applied along the earthquake acts, this means that, if it is necessary to calculate the input energy to an earthquake applied in the direction "x", modal coordinates and participation factors are used of the direction "X". Likewise, along the direction "Y" and "Z". When apply two accelerograms simultaneously in different directions, it is necessary calculates the input energy for each direction and sum both to obtain the total input energy.

4 NUMERICAL EXAMPLES

The churches built in Mexico during the Colonial Era, between the 16th and 18th centuries, are typical structures of unreinforced masonry. These buildings vary in size and in architectural style; however, it is possible to find a general basic typologies. An important factor which influenced the architectural style was the experience of the ancient builders due to the seismic activity of the country. Generally, in the Pacific's coast and more specifically in the State of Oaxaca, the recurrent destruction of the first constructions caused an evolution of the churches towards edifications of not much height, with big buttresses and little outer ornamentation. By this reason, the churches of Oaxaca are rectangular, with one nave. On the other hand, regions where the seismic activity is smaller, the churches remained higher and slender. It is the reason the churches of the State of Puebla are bigger, with a plant of Latin cross. Both churches have a simple façade that has attached one or two small towers

The façades are one of the most vulnerable parts of the churches due to the bell towers and their belfries. Hence, this section presents the analysis of two façades. These models do not belong to any particular church but are representative of the global features of churches in both states. Both façades were analyzed applying different earthquakes of significant magnitude that occurred worldwide in different dates. The structural analysis program SAP2000 was used to obtain the input energy of models and compare them with the proposed formula.

4.1 Models for analysis

Two finite element models were performed; which correspond to the typical churches of the states of Oaxaca and Puebla (Fig. 1). Geometrically, the façade of Oaxaca's church has a lower height than Puebla's. Other important difference that stands out is the height of the towers of the façade of Puebla. The towers are relatively higher compared to the central part of the façade. The finite element model of Oaxaca's façade has 1002 elements and 2204 degrees of freedom, whereas the Puebla's façade has 1578 elements and 3482 degrees of freedom. The mechanical characteristics of the masonry material are: Elascity´s modulus = 1962 MPa; mass density = 1600 kg/m3; Poisson´s ratio = 0.20.

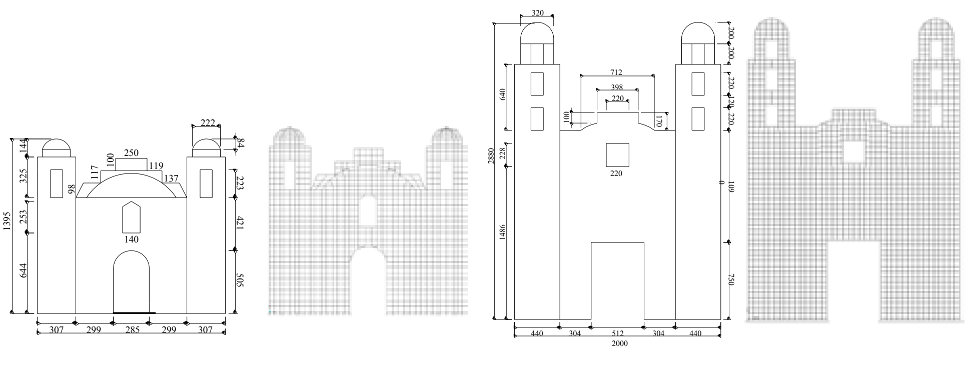

Figure 1: Dimension and finite element models of façades; State of Oaxaca (left), and Puebla (right).

Table 1 shows the modal characteristics of both façades. The Oaxaca's façade have a fundamental period lesser than Puebla's façade, but both have approximately equal participating mass ratios (Mass %). Considering only ten modes, mass percent is 90.73 to Oaxaca and 91.34 to Puebla. It is necessary to indicate that considering only the first mode, the response of facades will be not approximated. This shows that both facades are different in modal characteristics. Analyses of both façades showed the influence of the modal characteristics in the input energy.

Table 1: Modal characteristics of façades

	Oaxaca			*Puebla*		
Mode	*Period*	*MPF*	*Mass(%)*	*Period*	*MPF*	*Mass (%)*
1	0.12016	16.2058	61.43	0.26563	26.1514	61.95
2	0.08352	0.0002	0.00	0.17979	0.0001	0.00
3	0.05939	8.8028	18.13	0.13182	15.1881	20.90
4	0.04417	0.0036	0.00	0.08989	0.00012	0.00
5	0.04145	3.9645	3.68	0.08149	7.1166	4.59
6	0.03480	0.0068	0.00	0.05256	0.0001	0.00
7	0.02823	0.0045	0.00	0.04719	4.2646	1.65
8	0.02462	5.6116	7.37	0.04637	0.0010	0.00
9	0.02131	0.7029	0.12	0.03953	4.9854	2.25
10	0.02029	0.0005	0.00	0.03894	0.0003	0.00

4.2 Earthquakes

The façades were analyzed by applying the earthquakes of different sites of the world. Table 2 summarized the earthquake characteristics. These earthquakes differ in terms of location, magnitude, duration and peak ground acceleration.

Table 2: Earthquake Characteristics

Earthquake	*Site registration*	*Duration (s)*	*PGA (m/s2)*	*Magnitude*	*Event*	*Date*
Oax990615	Oaxaca	70.00	1.07	6.5	Puebla	15-VI-1999
Oax990930	Oaxaca	50.00	1.86	7.5	Oaxaca	30-IX-1999
Pue990615	Puebla	47.50	1.95	6.5	Puebla	15-VI-1999
Pue990930	Puebla	100.00	0.42	7.5	Oaxaca	30-IX-1999
Gem760915	Gemona	9.50	6.23	6.5	Friuli	15-IX-1976
Kob950116	Kobe	20.00	5.87	6.9	Kobe	16-I-1995
Sct850918	SCT. D.F.	90.00	1.75	8.1	Michoacan	18-IX-1985
Stu760506	Sturno	45.00	3.22	6.5	Friuli	6-V-1976
Tol760506	Tolmezzo	12.00	2.89	6.5	Friuli	6-V-1976
Bol991211	Bolu	16.00	8.07	7.3	Turkey	11-XII-1999

These accelerograms have different features that allow reviewing their influence on the structures. Some are very similar in time and other in acceleration. The largest peak ground acceleration is from Turkey, but it has shortest duration, compared to the rest of the earthquakes, that mean it is an impulsive earthquake motion. On the other hand, the

Pue990930 earthquake has longest duration, but the peak ground acceleration is lower.

4.3 Analysis and earthquake evaluation

Figure 2 shows the energy spectra for different earthquakes used. It can be seen for long-period structures, the SCT850918 earthquake demand much more energy than other earthquakes. This is consistent with the damage observed in 1985 in Mexico City, where the period of the structures was amplified by the soil type where they are built. Gem760915, Kob950116 and Bol991211 earthquakes are demanding greater energy for low-periods buildings (0.6-1.0s). Coincidentally these earthquakes also have the largest ground acceleration. Bol991211 earthquake motion has a longer duration and higher acceleration than the Gem760915 and Kob950116 earthquakes, but as it can see in Figure 2, it demanded less energy. This indicates that the duration and maximum ground acceleration are not parameters that dominated at all the energy input of structures. Fundamental periods is plotted to locate the energy demand on the façades, according the figure 2 (left) this would not have a high energy demand for any earthquake. The figure 2 (right) display a close up of the spectra that shows the location of both fundamental periods.

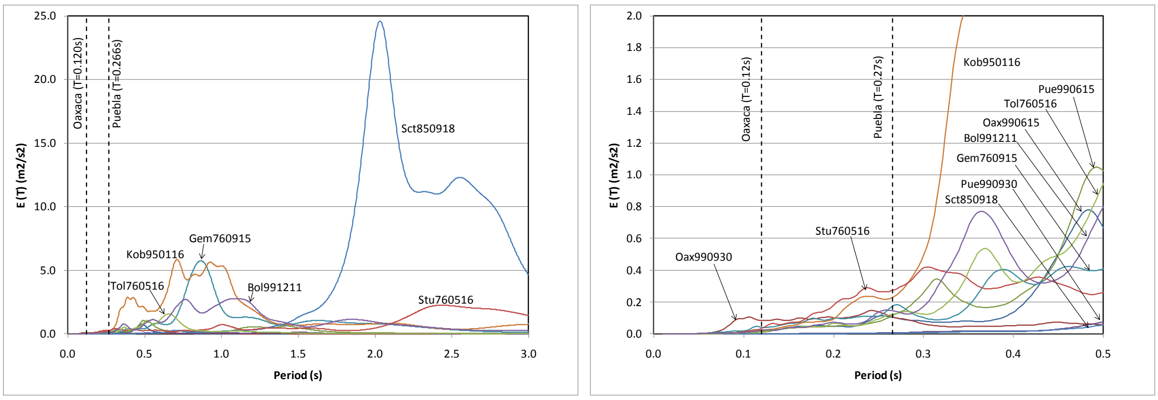

Figure 2: Spectra´s input energy of earthquakes (left), figure amplification (right).

Figure 3 shows, as an example, the energy of the earthquake in Bol991211 obtained with SAP2000 analysis program and the energy obtained with the proposed formula. The energy is not normalized, because the SAP2000 analysis program gave no normalized energies. As can be seen in the figure 3 the energy calculated with the formula 10 is near to the energy obtained with the SAP2000. It should be appreciated that the formula gives the energy at the end of the earthquake. The history of earthquake input energy shows a peak value around the 6s, which is slightly larger than the final input energy, the formula do not reflect those peaks. However, this increase is produced by the strain energy which is recoverable when elastic, but when the behavior is inelastic, peak strain energy is converted into hysteretic energy and reflected at the end of the duration of earthquake. The advantage of the formula is that it is possible to know the input energy at the end of earthquake duration, including all type of energies. Moreover, the formula can exclude the influence of mass; the normalized energy can be converted into equivalent velocity (Sucuoglu and Nurtug, 1995).

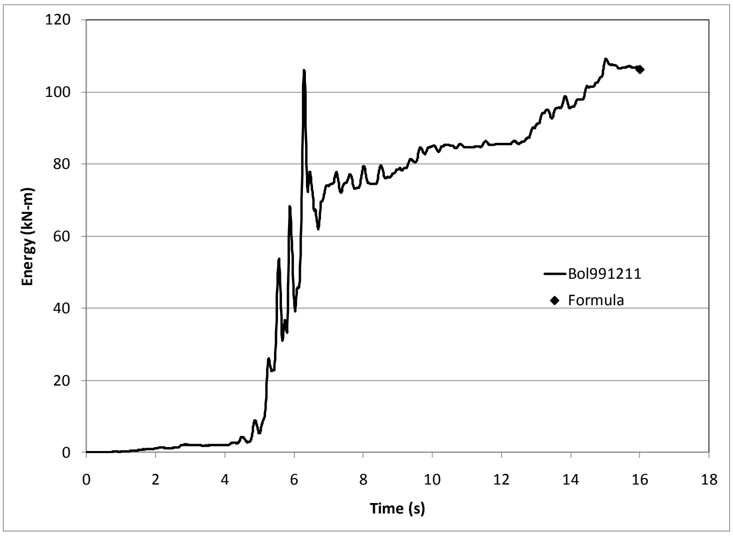

Figure 3: Comparison between energy obtained with the proposed formula and the SAP2000 software

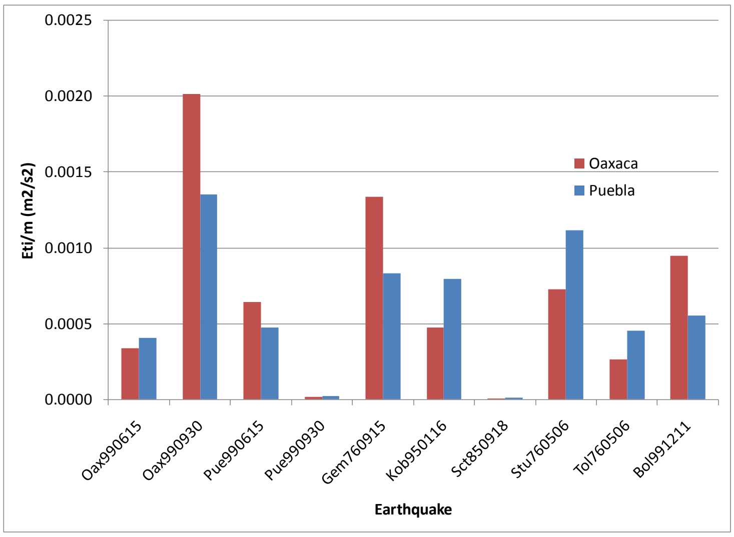

Figure 4: Demand of energy for the façades from Oaxaca and Puebla

Figure 4 shows the energy demand for both façades, obtained with the proposed formula. The highest energy demand was caused by the Oax990930 earthquake. On the other hand, the Sct850918 earthquake demands lowest energy. The Oax990930, Pue990615, Gem760915 and Bol991211 earthquakes had higher destructiveness potential on the Oaxaca´s façade. The Oax990615, Pue990930, Kob950116, Sct850918, Stu760506 and Tol760506 earthquakes demand high energy to Puebla's façade. According to results and the earthquake magnitude (Table 2), there are no relation between input energy and earthquake magnitude. All of them have an approximated magnitude of 7.5, but the input energies are not approximated. Table 3 shows the comparison between both input energies. The error between the SAP2000 program and the formula is in the range 0 to 10%. Energies obtained with the code SAP2000 were always bigger than the formula. Because the formula considers only the 90% of the mass of the structure at take into account only ten modes. However, the results between both were very approximate and can be considered equal. It is clear that taking more modes in the calculations, the error will tend to zero.

Table 3: Comparison of input energy

	Oaxaca			*Puebla*		
Case	*Formula*	*Sap2000*	*Error (%)*	*Formula*	*Sap2000*	*Error (%)*
Oax990615	4.01	4.10	2.20	76.17	76.61	0.57
Oax990930	21.96	22.87	3.98	94.70	96.20	1.56
Pue990615	3.69	3.78	2.38	84.60	85.04	0.52
Pue990930	0.14	0.14	0.00	4.90	4.93	0.61
Gem760915	11.16	11.43	2.36	130.81	131.57	0.58
Kob950116	5.55	5.99	7.34	163.63	166.48	1.71
Sct850918	0.07	0.07	0.00	3.25	3.29	1.22
Stu760506	9.32	9.51	2.00	202.86	204.00	0.56
Tol760506	2.72	2.77	1.81	89.94	90.40	0.51
Bol991211	6.67	6.84	2.49	106.27	106.86	0.55

5 CONCLUSIONS

A novel formula to assess the destructiveness potential of earthquakes by using the input energy was proposed. It is very easy to calculate the maximum energy input with the proposed formula, because only needed the modes of vibrating of the structure and the energy spectrum.

The results showed that an earthquake not have the same destructiveness potential for two different structures. The duration and maximum acceleration of an earthquake are not parameters that dominate at all the energy input of structures. In general, the proposed formula to calculate the input energy gave a much better approximation than the modal time-history analysis. The proposed formula to calculate the input energy is only valid for the linear elastic range, since the formula does not include damage and elastic energy spectrum is used.

ACKNOWLEDGEMENT

The first author acknowledges the Ph.D. grant of Consejo Nacional de Ciencia y Tecnología – CONACyT of Mexico.

REFERENCES

[1] Akiyama, H., Earthquake-resistant Design Method for Buildings Based on Energy Balance, Gihoudou, Syuppan Press. (1999).

[2] Arias, A. A measure of earthquake intensity. *Seismic Design for Nuclear Plants*. R.J. Hansen ed., MIT Press, Cambridge, MA. (1970) 438–469.

[3] Housner, G.W. Spectrum intensities of strong motion earthquakes, *Proc. Symp. of earthquake and blast effect on structures*, EERI, Los Angeles, CA. (1952) 835–842.

[4] Lourenço, P. Computations on historic masonry structures, *Prog. Struct. Engng Mater.* (2002) **4:**301–319.
[5] Sucuoglu H. and Nurtug A. Earthquake ground motion characteristics and seismic energy dissipation, *Earthq. Eng. Struc. Dyn* (1995) **24**:1195–1213.
[6] Uang, C. and Bertero, V. Evaluation of seismic energy in structures. *Earthquake Engineering and Structural Dynamic* (1990) **19**:77-90.
[7] Orosco, L. and Alfaro, I. Potencial destructivo de sismos (segunda parte). Notebook of Engineering faculty, Universidad Nacional de Salta, Salta, Argentina, (2008) 34–45.