Seismic Damage Prediction of Reinforced Concrete Building Structures based on the Energy Balance Method

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MEE06010

ABSTRACT

The Energy Balance Method is presented and applied to the analysis of reinforced concrete structures; the seismic demand is represented by the damage input energy which is directly related to the Pseudo-velocity spectrum found in many of the current seismic codes, several factors that influence the distribution of the energy in the structure, such as the damage concentration factor and the relationship between ductility and cumulative plastic deformation, are studied in more depth, finally illustrative examples of moment resisting frames and frames with hysteretic dampers analyzed by the Energy Balance Method are presented; these examples show good agreement of the results when compared to other analysis methods that are widely adopted in many seismic codes such as the Capacity Spectrum Method and the Nonlinear Time History Analysis.

Keywords: Energy Balance, Seismic Design, Reinforced Concrete Structures, Hysteretic Dampers.

INTRODUCTION

The earthquake resistant design methodology in most countries is regulated by the National Seismic Code or Building law, most of these codes use force based design procedures, these procedures establish that in order to calculate the force that an earthquake induces in the structure, a base shear needs to be calculated; this shear is obtained by multiplying the weight of the structure by a seismic coefficient.

One fundamental issue that is not taken into account in current design practice is the earthquake energy input to the structure, earthquake input energy accounts for both the ground motion characteristics (frequency content, intensity, and duration of strong motion) and structural properties (ductility, damping, period, and hysteretic behavior), whereas PGA, EPA, etc. account for some but not all these characteristics.

The Concept of Energy has been studied by many researchers but the basic theory was proposed by G. Housner (1956) and later was developed and extended by H. Akiyama (1985), most of the work has been done for steel structures, therefore more investigation into RC structures is needed.

This concept is based on the premise that both the demand of energy due to a ground motion and the energy supply of a structure can be established, therefore a satisfactory design implies that the energy supply must be larger than the energy demand.

This research is aimed towards the development of a methodology for the design and prediction of damage of reinforced concrete structures subjected to earthquakes according to the energy balance theory, in order to achieve this objective several specific topics have to be studied such as, the applicability of the energy spectrum to reinforced concrete structures using nonlinear models, the influence of the beam to column strength ratio in the damage concentration, the relationship between the maximum ductility μ and the average cumulative plastic deformation $\bar{\eta}$, and finally the response prediction based on the energy balance method using analytical models.

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THEORETICAL BACKGROUND

The equation of motion for a structure subjected to a horizontal ground motion at the base were *M* is the mass of the system, *C* the damping, *F(u)* the restoring force on the spring and $\ddot{u}_g$ the horizontal ground acceleration, can be expressed in an energy form according to equation (1).

$$M\int_0^{to} \ddot{u}\,\dot{u}dt + C\int_0^{to} \dot{u}^2\,dt + \int_0^{to} F(u)\,\dot{u}dt = -M\int_0^{to} \ddot{u}_g\,\dot{u}dt \qquad (1)$$

The term on the right hand side of equation (1), represents the total input energy *E*, on the left side, the first term represent the kinetic energy E_k, the second is the energy consumed by damping E_d and the third is the strain energy E_s, the strain energy is composed of cumulative plastic strain energy E_p and elastic strain energy, the elastic strain energy and the kinetic energy represent the elastic vibration energy of the system E_e, Housner (1956) assumed that in elastic-plastic systems, the damping energy does not contribute to the damage of the structure, therefore the following equation holds:

(2)

$$E_p + E_e = E_D \leq E_H$$

It has been demonstrated that the energy input into a structure is a very stable parameter that is exclusively dependant of the natural period and the weight of the system. The total energy *E* and the energy attributable to damage E_D can be converted into equivalent velocities as follows:

$$V = \sqrt{((2\,E)/M)} \qquad (3)$$

Damage Distribution

The energy attributable to damage E_D has to be absorbed by the structural elements without suffering excessive damage in order to have a safe design, this damage energy has to be distributed to every story of the structure, small changes in strength and/or stiffness between resisting elements in different stories will cause an energy concentration in the weak portion of the structure, this concentration will lead to undesirable behavior of the structure and possible collapse, in this study the damage distribution proposed by Akiyama (1985) will be used,

Energy Balance Method for the Analysis and Design of Structures

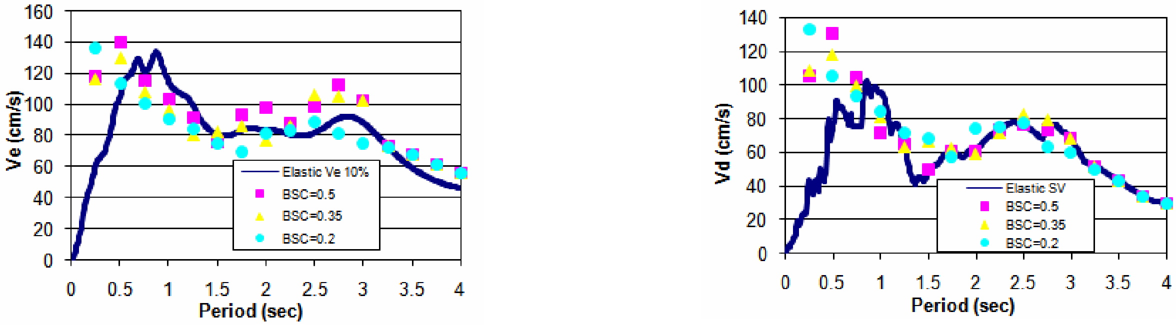
The energy balance method basically consists of 5 steps,

1. Determine the total damage input energy.
2. Determine the elastic energy that the structure can absorb.
3. The difference between the energy from step 1 and 2 is the plastic energy.
4. Distribute this plastic energy to every story in a rational way. (Distribution law)
5. Convert the plastic energy in each story into displacement and check with the code limits.

Some important parameters of this method are studied in more depth through the report; also this procedure is implemented to analyze various types of model structures.

ENERGY INPUT INTO REINFORCED CONCRETE STRUCTURES

As was shown previously, the total energy can be transformed into an equivalent velocity, by using a numerical procedure to solve the equation of motion; we can calculate the total input energy of a ground motion for several SDOF systems with different natural periods and a certain damping factor and plot an equivalent velocity spectrum, according to Akiyama (1985), the equivalent velocity V_E that needs to be used to check the ultimate strength of structures against earthquakes can be obtained by the envelope of the velocity spectrum of an elastic system with a 10% damping factor, this premise was established after the comparison of the response of several Elastoplastic SDOF systems, also Housner (1956) assumed that V_{max} was the upper bound of the damage energy, this assumption was validated by Akiyama for Elastoplastic systems, therefore we shall determine is this is true for hysteresis models that represent the behavior and damping of RC structures.



El Centro NS

Figure 1, Total Velocity V_E Spectra and damage velocity for Takeda Model, Damping 3%

In figure 1 we can observe that the values of total input energy represented by the equivalent velocity of the model with a damping factor of 3% are approximated by the elastic V_E spectrum for 10% damping factor, also when plastification occurs, the natural period of the structure is amplified, and it was found that the damage energy values of structures with the amplified period can be predicted by the pseudo velocity spectrum which is available in every seismic code. (It can be obtained from the acceleration spectra)

INFLUENCE OF BEAM-COLUMN STRENGHT RATIO ON THE DAMAGE CONCENTRATION IN REINFORCED CONCRETE STRUCTURES

The influence of the beam to column strength ratio $\boldsymbol{R_c}$, on the damage concentration is investigated, this is very important because the beam to column strength ratio determines the type of collapse mechanism of the structure, in order to determine the damage concentration factor *n*.

The ratio of the plastic energy of each story to the total plastic energy in a given story *i* can be computed is denoted as *a*, then the strength of the story *i* is deliberately reduced by multiplying the strength by a factor p_d, in this case we will use p_d=0.8 in the third story of our 5 story model, the ratio of the plastic energy of each story to the total plastic energy in the story *i* can be computed is denoted as *b*, from these two cases, the damage concentration factor *n* can be obtained.

This procedure was carried out for 8 different values of column to beam strength ratios R_c varying from 0.8 which is a weak column system, to 1.5 which is a weak beam system, for 3 types of nonlinear behavior and for 3 ground motion records scaled to a maximum velocity of 50 kine. (See figure 2)

We can obtain the damage concentration factor *n*, from these analyses we can plot the damage concentration factor as a function of the beam to column strength ratio R_c as shown in figure 3.

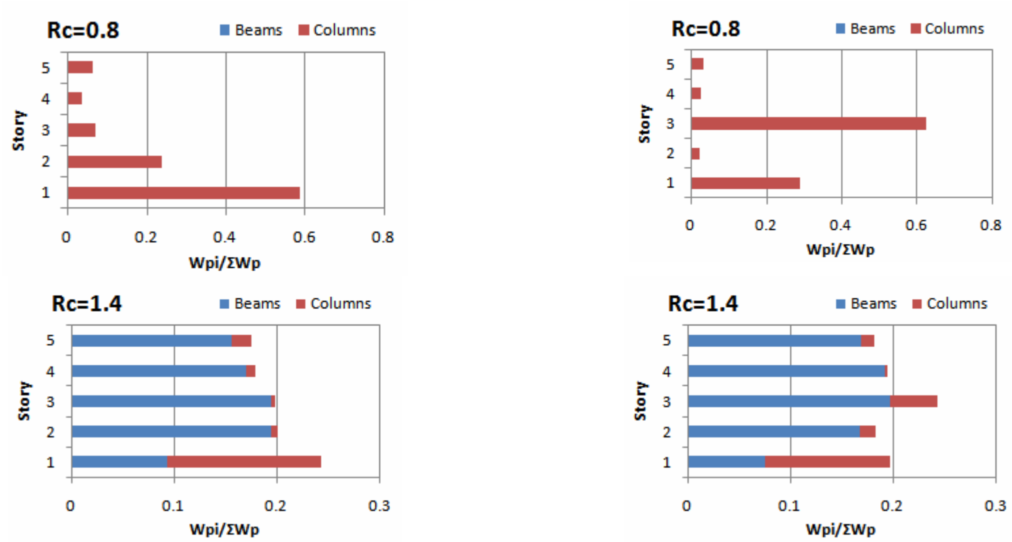


Figure 2, Distribution of Plastic Energy, Degrading Trilinear Model, El Centro NS, Left Column pd=1.0, Right Column pd=0.8 in the 3rd story.

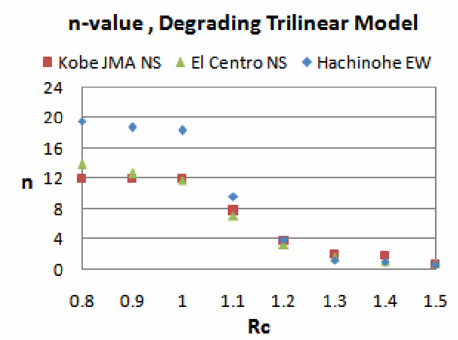


Figure 3, Damage concentration factor *n*

RELATIONSHIP BETWEEN DUCTILITY AND AVERAGE CUMULATIVE PLASTIC DEFORMATION FOR REINFORCED CONCRETE STRUCTURES

To determine the relationship between the equivalent frequency of plasticity and the ductility of a structure an analysis was carried out for the 3 ground motions and the 3 types of hysteresis models that have been used in the previously, it's important to mention that the ground motions used were scaled to have an equivalent damage velocity V_D equal to the pseudo velocity obtained using the Costa Rica Seismic Code design spectrum as shown in figure 4, this was done with a special function of the program Shearms developed by Professor Ogawa from Kumamoto University.

In the earthquake response analysis, the plastic energy of each story is determined and the average cumulative plastic deformation ratio $\bar{\eta}_i$ is obtained, also the ductility μ of each story can be easily obtained dividing the maximum displacement by the yield displacement; we must obtain the value of μ-1 because we are only interested in the inelastic part of the deformation, for each story, a relationship between μ-1 and $\bar{\eta}_i$ can be obtain, the relationship between these two parameters represents the equivalent frequency of plasticity of the story *i* P_{ef}.

From the earthquake response analysis performed to several building models we can conclude that a value of equivalent frequency of plasticity P_{ef} of 2.0 can be used for normal level earthquakes, and 2.3 for strong level earthquakes in reinforced concrete structures, in the case of Elastoplastic response that happens mainly in steel buildings, the average values are lower than the degrading hysteresis models, therefore the designer should take this into account when analyzing a structure, its important to observe that the smaller the value of the equivalent frequency of plasticity P_{ef}, a larger value of displacement is obtained therefore a conservative design is achieved.

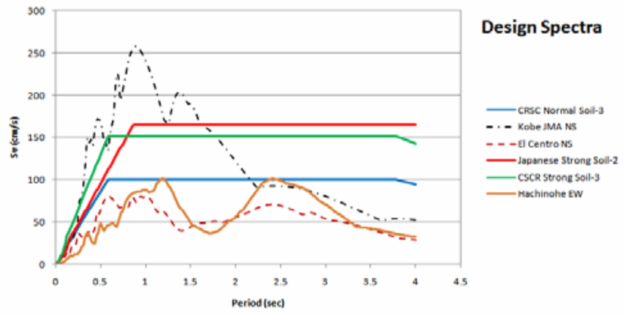


Figure 4, Pseudo-Velocity Spectra

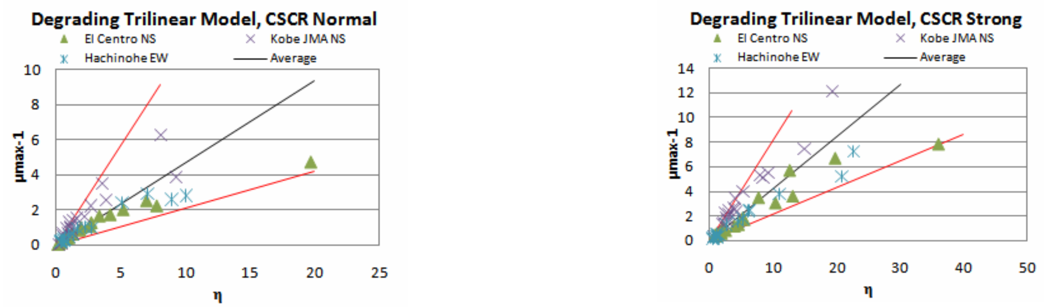


Figure 5, Correspondence between maximum ductility μ-1 and average cumulative plastic deformation $\bar{\eta}$.

PRACTICAL APPLICATION OF THE ENERGY BALANCE METHOD

Two model buildings are used in this chapter to evaluate the Energy Balance Method; both buildings have the same plan configuration (in the X direction 3 bays of 7 m and in the Y direction 3 bays of 6 m) but one is 8 stories and the other one is 4 stories (3.5m high), both were designed according to the Costa Rica Seismic Code.

A nonlinear static pushover analysis of the two building models was done using the program Stera 3D developed by Dr. Taiki Saito, for each model and for each story a force displacement curve was obtained, and the values of the most important parameters, like cracking, yielding and ultimate force and displacement were obtained by a procedure of equivalent linearization, these properties were used in the energy balance procedure mentioned previously in order to predict the interstory drift of the structure.

The computer program Stera 3D was used to obtain the earthquake response of the structure, the analysis was carried out for 3 ground motion records scaled in order to produce an equivalent velocity equal to the pseudo velocity obtained using the Costa Rica Seismic Code design spectrum this is done with a special function of the program Shearms.

After performing the analysis of the building models with all the procedures mentioned before, the final results for interstory drift were obtained and compared.

The analysis procedure for a structure with hysteretic dampers is basically the same as for a regular frame structure; this method was described previously, although some parts must be modified in order to take into account the damper system.

As mentioned before the values from the Time History Analysis will be treated as the exact value for comparison purposes.

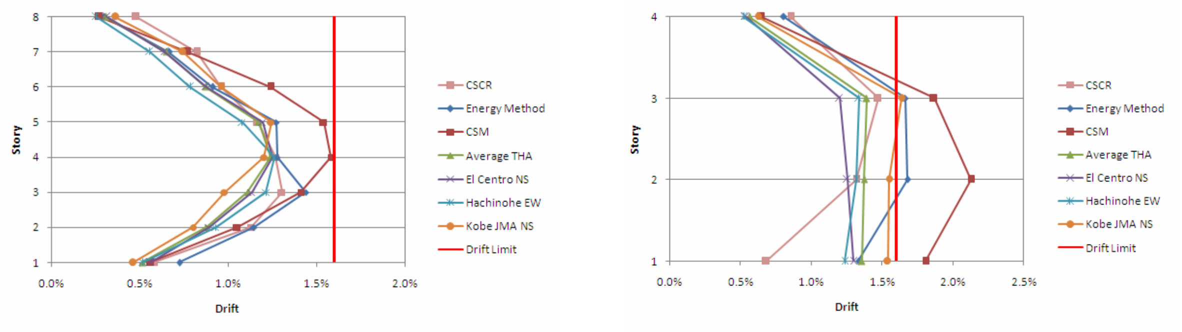


Figure 6, Maximum Drift Values

According to the results obtained we can observe that the Energy Balance method is in the safe side of the approximation of the interstory drift of the “exact” THA procedure whereas the Capacity Spectrum Method seems too conservative.

This result validate the use of the Energy Balance Method as an alternative way to predict the seismic damage in reinforced concrete structures, and also has the benefit of being able to be implemented very easily into any design code since the input data can be obtain directly from the pseudo velocity design spectra.

CONCLUSIONS

The Energy Balance Method has been explained and applied to model structures in order to predict the damage in reinforced concrete structures produced by an earthquake, some conclusions are presented next

- The input energy represented by the equivalent velocity spectra and damage energy represented by the pseudo velocity spectrum; can be applied to reinforced concrete structures.
- The damage concentration and the collapse mechanism in structures is highly dependant on the beam to column strength relationship R_c.
- For values of R_c = 1.4 or higher, there is practically no damage concentration in the structure when one story changes suddenly its strength.
- From a series of nonlinear time history analysis it was found that for a normal type of earthquake a value of equivalent frequency of plasticity P_{ef}= 2.0 is appropriate while for a strong earthquake a value of 2.3 must be used.
- The Energy Balance Method (EBM) was applied to model structures with and without hysteretic dampers, and it was found to be in good agreement and on the safe side with the results of Nonlinear Time History Analysis (NTHA).

ACKNOWLEDGMENT

Professor Ogawa of Kumamoto University for letting me use his programs FISH and SHEARMS, also Dr. Saito who answered all of my questions and also provided me with many computer programs to use in my study.

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