

## Analytical Evaluation of the Structural Seismic Damage of Reinforced Concrete Frames

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### ABSTRACT

In this paper different definitions of global and local damage indexes and earthquake intensity are investigated to evaluate the seismic performance of building structures. As an example, the seismic performance of a 10-storey building located in the Lake Zone of Mexico City, damaged during the 1985 Michoacan earthquake, is evaluated when subjected to the actual 1985 record and to a set of synthetic records that simulate a seismic environment in the zone where the structure is located. The results of detailed dynamic nonlinear analyses show that, for regular buildings, these damage indexes bear high correlation with different measures of earthquake intensity. This makes it possible to suggest practical ways to estimate the expected structural damage of reinforced concrete buildings when subjected to earthquakes of different intensities.

### INTRODUCTION

The recent occurrence of destructive earthquakes in large urban areas has led to changes in seismic codes which have modified, sometimes drastically, the seismic risk of existing buildings. Under these circumstances, the problem of the evaluation of seismic capacity and seismic damage of damaged and undamaged reinforced concrete buildings has become of paramount importance. The analytical investigation of structural damage is of relevance in the design of new structures, the evaluation of the performance of existing damaged and undamaged structures, the repair and retrofitting requirements and the seismic vulnerability required for establishing plans for disaster prevention and safeguard for a region.

The current practice of seismic evaluation of buildings is largely based on the ductilities demanded by the different elements of a structure. Unfortunately, the use of ductility as a performance index has been questioned. Hence the need for more general indexes to characterize structural performance. Extensive research has produced several indexes, referred to in the literature as damage indexes, that need to be evaluated with real structures. This paper is concerned with the evaluation of some of these indexes. The validity of these indexes is shown from the analysis of the responses of a real structure subjected to a family of earthquake records of different intensities.

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## DAMAGE INDEXES IN STRUCTURAL PERFORMANCE EVALUATION

An extensive review of the literature on damage indexes carried out by Escobar and Ayala (1994) shows that, regardless of the numerous existing definitions, not a single one involves all the relevant parameters in structural damage. Damage indexes could be of local or global nature with some of the global measurements based on weighted combinations of local damage indexes.

In this paper two different kinds of damage indexes are evaluated:

(I) Local Damage Index. The most widely used definition of local damage index, proposed by Park and Ang (1984), reflects cumulative effects and is a combination of the normalized maximum inelastic deformation and the energy dissipated through hysteresis. This definition can be expressed in terms of moment and curvature as

$$D = \frac{\theta_m}{\theta_u} + \frac{\beta}{\theta_u M_y} \int dE \quad (1)$$

where  $\theta_m$  is the maximum inelastic curvature during the load history,  $\theta_u$  is the ultimate curvature of the section,  $\beta$  is the weighting factor for the energy dissipated,  $M_y$  is the yield moment of the section and  $E$  is the dissipated hysteretic energy.

The behaviour of this index is highly dependent on the hysteresis model chosen for the element as the parameter  $\beta$  is sometimes assumed to be the same as that of the hysteresis model proposed by Park, Reinhorn and Kunnath (1987). These authors have suggested a modification to the definition given in eq 1 by removing the recoverable curvature from the deformation contribution of the model, that is

$$D = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} \int dE \quad (2)$$

where  $\theta_r$  is the recoverable rotation at unloading

Local damage indexes have been used to calculate interstorey and global damage indexes as weighted combinations of the indexes corresponding to each element. Weighting factors are defined as functions of the hysteretic energy dissipated by each element. Extensive evaluation of the evolution of local and global indexes so defined has been carried out for structures and different seismic environments, Ye (1995). The results of this evaluation show that the Park and Ang index does not represent properly the effect of hysteretic energy dissipation for structures subjected to earthquakes as those occurring in the Lake Zone of Mexico City. Furthermore, the way that the interstorey and/or global damage indexes are calculated is not reliable. It neglects the relative importance of each structural element to the stability of the structure. The definition of weighting factors does not consider whether the element is a beam or a column. In this investigation a more refined approach based on the sensitivity matrix of the structure, is studied.

(II) Global damage index. Due to difficulties found in the definition of global damage index, in this paper, the two alternative definitions proposed by DiPasquale and Cakmak (1988), are investigated. These indexes are based on measures of change in the fundamental period of the structure due to changes in stiffness induced by earthquake action. The first of these indexes is defined as

$$D_m = 1 - \frac{T_0}{T_{\max}} \quad (3)$$

where  $T_{\max}$  is the maximum fundamental instantaneous period reached during the response of the structure and  $T_0$  is the initial period.

The second index, referred to as final softening, is defined as a function of the initial fundamental period  $T_0$  and the final period  $T_{\text{final}}$ , i.e.

$$D_f = 1 - \frac{T_0^2}{T_{\text{final}}^2} \quad (4)$$

This index represents the change in stiffness relative to the initial condition.

The evaluation of these indexes, Ye (1995), has shown poor correlation with all analyzed definitions of earthquake intensity. Thus, in this paper, a new damage index, also based on fundamental period changes, is investigated. This index is defined as

$$D_t = \frac{T_{\text{final}} - T_0}{T_u - T_0} \quad (5)$$

where  $T_u$  is the fundamental period associated with a selected limit state of the structure. In this investigation this period was the largest obtained from a push over analysis.

## SEISMIC INTENSITY

The performance of a structure needs to be related to a measurement of seismic intensity. There exist numerous definitions of intensity but so far none has been proved to be of relevance to damage evaluation. An effort to find the most adequate definition of intensity related to expected damage has been made by Escobar (1994). The reported results are not conclusive. So in this investigation the problem was revisited by studying the relation of damage indexes to seven definitions of intensity. Those considered were (Uang and Bertero, 1988) peak ground acceleration (PGA); modified Housner elastic and elastoplastic velocity response spectrum intensity (Sve and Svp); Housner earthquake power intensity (PA); Arias intensity (IA) and modified Arias intensity (PD). The modified Housner elastic and elastoplastic velocity response spectrum intensities are modifications of the original definition taking into account large periods in the records in the Lake Zone and that damage is always associated to nonlinear behaviour, Ye (1995).

## EVALUATION OF DAMAGE INDEXES

(I) Nonlinear analysis tools. The determination of the nonlinear dynamic response of building structures is a complex problem which involves not only the development of correct computational algorithms but also the use of adequate behaviour models for the structural elements. Three computer programs were validated, DRAIN2-D, IDARC and CANNY, Kanaan and Powell (1972), Kunnath et al (1992) and Li (1993). The procedure was carried out using different frames with results that show the importance of the selected behaviour model on nonlinear response. Comparing responses, it was found that, in most cases IDARC and CANNY gave similar results. In this paper, only the results from IDARC are presented.

(II) Example structure. As a test structure, a plane frame of an existing reinforced concrete regular building designed in accordance with the 1966 code was used. The building is located in the Lake Zone of

Mexico City and was damaged by the 1985 earthquake, Meli and Avila (1988). Fig 1 shows frame configuration, location of observed damage and location of damage obtained from the analytical model.

(III) Seismic excitations. Earthquake records used in this investigation were chosen as representative of a seismic environment in the Lake Zone. The set was formed by the E-W component of the SCT record and eleven simulated records of several intensities, Grigoriu , Ruiz and Rosenblueth (1988).

## PRESENTATION AND ANALYSIS OF RESULTS

For calibration the frame of Fig 1a was subjected to the E-W component of the SCT record. Figs 1b and 1c show the corresponding distributions of observed and calculated hinges. It may be observed that there is a fair similarity between these two figures. The existing differences may be attributed to the behaviour model used and to the fact that the record used was not that of the earthquake which actually damaged the structure because a strong motion instrument was not at or near the site.

Figs 2a to 2d show the distribution, with story, of different response parameters obtained from the nonlinear dynamic analysis of the example frame. Fig 2e shows the corresponding distribution of the interstorey damage index calculated as the weighted sum of local damage indexes with weights defined as functions of the energy dissipated by hysteresis in the corresponding elements. From these figures it may be observed that there is no apparent correlation between the interstorey damage indexes and the selected response parameters. For reference purposes, Figs 2a to 2d also show the corresponding response parameters from a linear analysis.

Regarding the evolution of the global damage indexes, Figs 3a to 3d show the corresponding time histories for the SCT ground acceleration, the roof displacement, the Park and Ang global index and the instantaneous fundamental period. In Figs 3b to 3d it may be observed that most of the damage occurs in the intense part of the earthquake and the Park and Ang index does not seem to give the proper weight to the energy dissipated by hysteresis. Fig 2d shows an initial period of 1.18 sec and a final of 2.66 sec which is larger than the 2.1 sec measured in the building after the earthquake. The larger value for the theoretical period can be attributed to the fact that the period was measured once the building was stripped and that real strengths are generally larger than the nominal value used in the analyses.

The correctness of the results of Fig 2 was checked comparing the displacement histories with those obtained using programs CANNY and DRAIN2-D. For all cases IDARC's results were comparable to those obtained with CANNY and were more than 20% greater than those from DRAIN2-D. This observation shows the importance of the computational tool in the obtained results.

To evaluate the relationship of different intensity measures with the global damage indexes evaluated in this investigation, the example structure was subjected to the complete family of records. Figs 4 and 5 show the variation of these indexes with different intensities. It may be seen that the best correlation occurs for the index proposed in this paper with the modified Arias intensity. In these figures results for El Centro and Taft earthquakes are also presented. Lack of damage shows the importance of earthquake characteristics upon structural damage.

## CONCLUSIONS

The almost linear relationship between the damage index proposed in this paper and the modified Arias intensity offers a simple method to characterize seismic performance (measured by a global damage index) as a function of earthquake intensity. This damage index is important as damage is defined as a function of a limit state selected by the engineer in charge of the evaluation. The index here proposed does not give information about damage distribution, for this, a method based on the change in the fundamental mode shape is under investigation.

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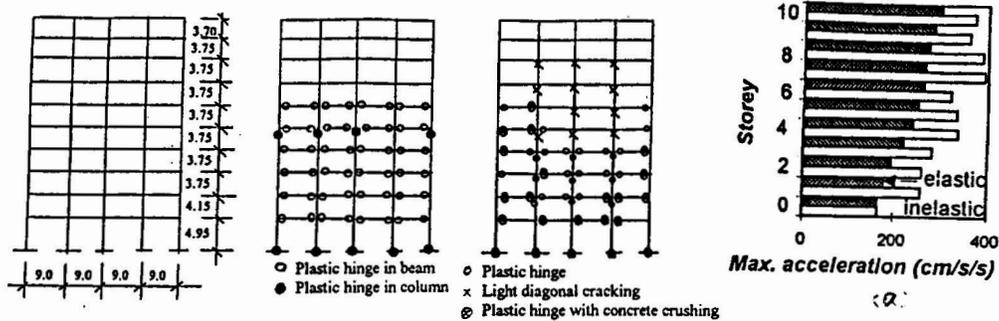


Fig 1a. Elevation of the example frame Fig 1b. Plastic hinges in the frame obtained from analysis Fig 1c. Schematic pattern of damage the frame obtained from analysis (after Meli and Avila, 1988)

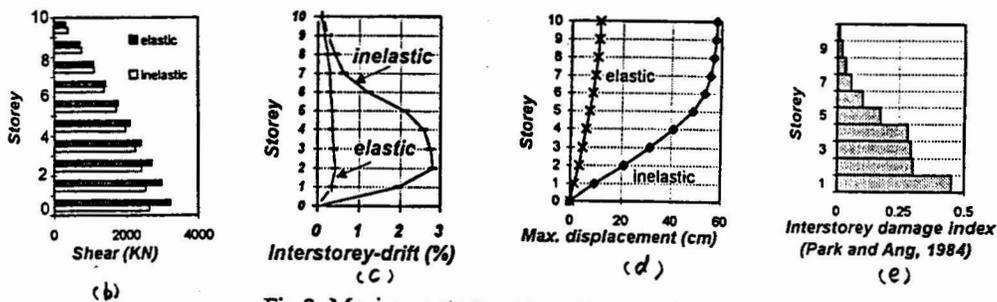


Fig 2. Maximum storey response parameter

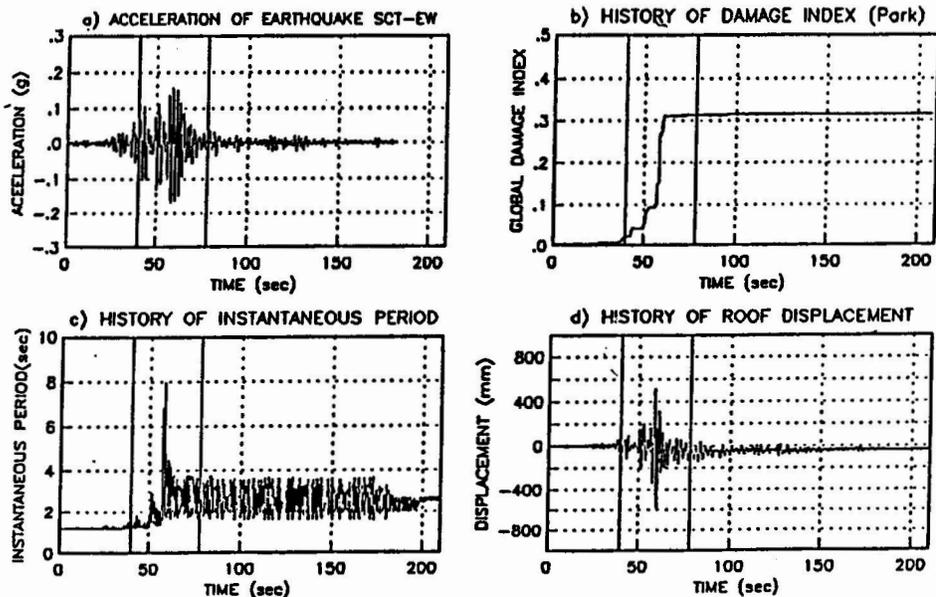


Fig 3. Time history of response parameter

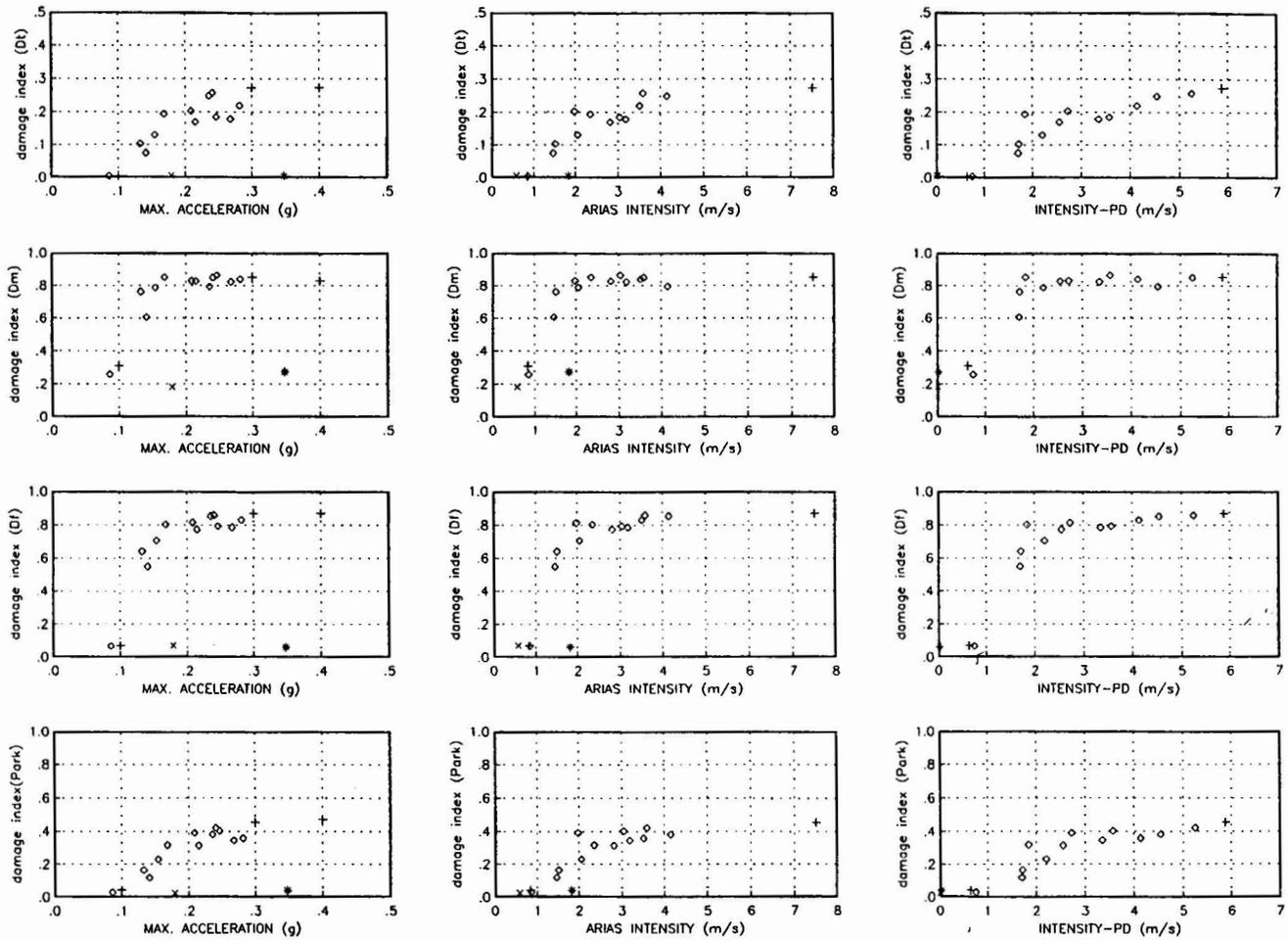


Fig 4. Relation between damage indexes and seismic intensities

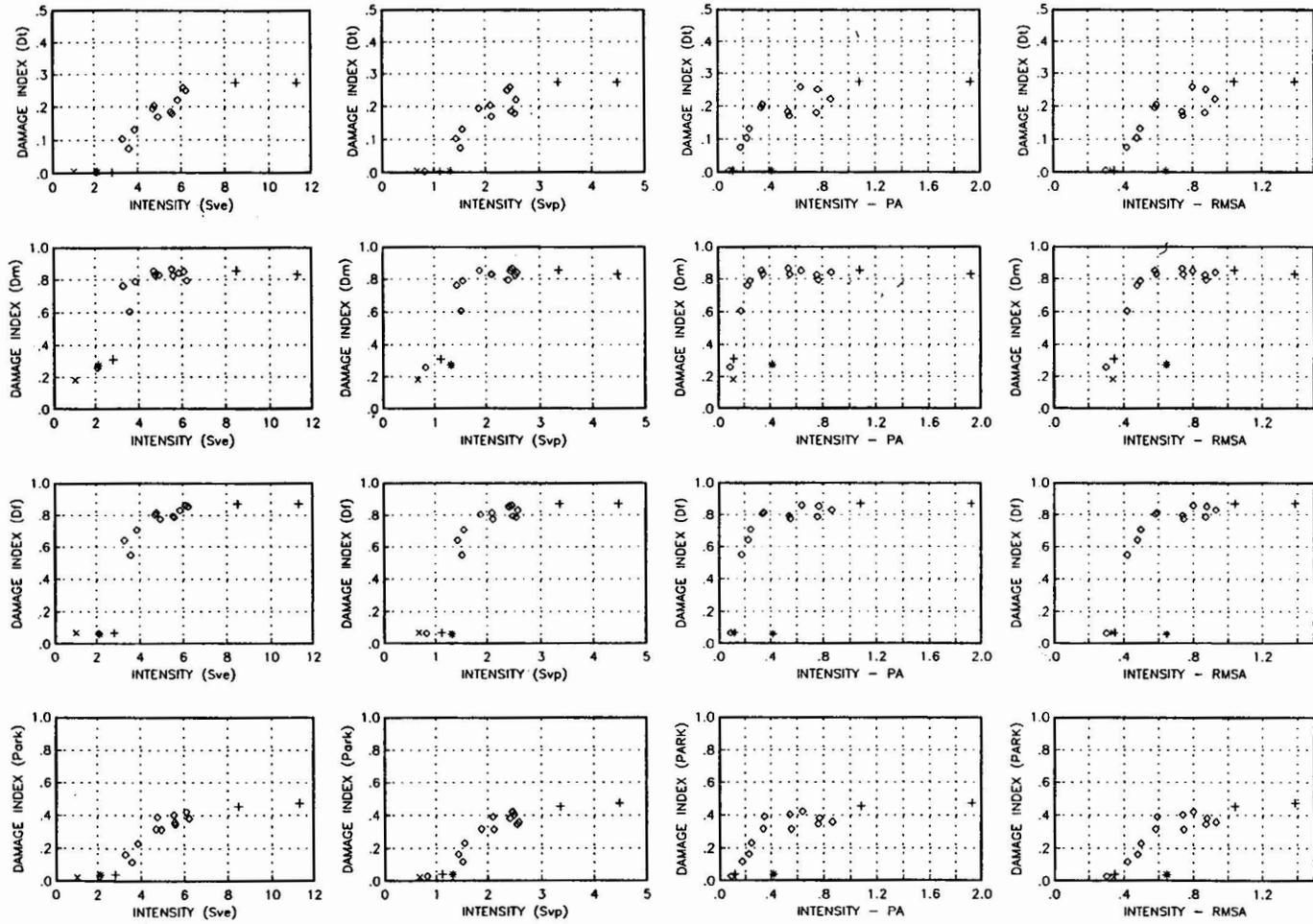


Fig 5. Relation between damage indexes and seismic intensities (cont.)