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ANALYSIS OF THE BEHAVIOR OF BUILDINGS DURING THE 1994, NORTHRIDGE EARTHQUAKE

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ABSTRACT

Evaluated in this study is the behavior of eight buildings during the 1994, Northridge, earthquake using recorded building motions. The "recorded" behavior is first compared with theoretical predictions based on nominal, three-dimensional, linear building models. Results show that the predictions based on these models are in most cases inaccurate. Because of this, a recently developed simplified inelastic procedure, which uses ultimate story shear and torque surfaces, is successfully tested and formulated as an alternative to conventional linear models. Finally, instrumentation and building analysis and design issues are discussed in light of the results generated in this research.

KEYWORDS

Building models; building records; model uncertainty; single element model; story shear and torque

INTRODUCTION

The 1994 Northridge earthquake has produced one of the most valuable databases of ground and earthquake building responses in history. A total of 193 stations of the California Strong Motion Instrumentation Program recorded 116 free-field ground motions and 77 structural responses. From the latter, 57 correspond to buildings records obtained for a wide range of structural configurations. The seismic performance of eight of these buildings, the ones most strongly shaken, are studied in this investigation. In particular, the objectives are to: (1) evaluate the uncertainty present in conventional structural linear building models; (2) evaluate the deficiencies in current procedures for earthquake analysis and design, and (3) propose improved analysis and design procedures calibrated using "measured" responses.

BUILDINGS CONSIDERED AND RECORDED MOTIONS

The buildings considered in this study are listed in Table 1. They cover a wide range of structural systems in use today, such as R/C frames, precast R/C walls, R/C column-flat-slab frames, steel bracings, steel walls (uncommon), and mixed R/C and steel frame systems. Notice that for all these structures the peak ground accelerations during Northridge exceeded $0.2g$. Shown in Fig. 1 are the recorded acceleration components at the base of each building in the East-West direction. In this study the buildings are ordered according to distance to the epicenter, A being the closest and H the farthest.

Table 1 Buildings considered

CSMIP Station	Building	Number of Stories	System	PGA x-direction	PGA y-direction
24386	**A**: Van Nuys (hotel)	7	R/C frame	0.44g	0.37g
24514	**B**: Sylmar (hospital)	6	R/C, steel frame,walls	0.52g	0.67g
24231	C: UCLA (Math-Science)	7	R/C walls, steel frame	0.25g	0.29g
24332	**D**: LA (commercial)	3/2	Braced frame	0.33g	0.32g
24385	**E**: Burbank (residential)	10	R/C precast walls	0.27g	0.29g
24370	**F**: Burbank (commercial)	6	Steel frame	0.25g	0.29g
24652	**G**: LA (office)	5/1	Braced frame	0.24g	0.20g
24463	**H**: LA (warehouse)	5/1	R/C frame-flat slab	0.20g	0.26g

ANALYSIS OF BUILDING RECORDS

In order to clearly identify the building behavior, recorded motions were subjected to four different analyses: (1) non-parametric identification---used to estimate apparent vibration frequencies and modes of each building, (2) time-frequency analysis---used to identify nonlinearities in a building's response, (3) story shears and torque analysis---used to interpret inelastic behavior of the building and construct the inelastic SEM (single element) model defined later, and (4) story force-deformation analysis.

Shown in Fig. 2 are typical results of this phase of record processing; the results selected in this case are for building A. Non-parametric identification is presented in Fig. 2a, where the frequency response function between ground motion and roof response is presented for the x,y, and θ directions--the top two rows represent transfer functions at the roof and midheight; the bottom row represents just the spectrum of the input. Results of time-frequency analysis of the same building are presented in Fig. 2b; in this case, the analysis was done also for other four motions recorded on the building during previous earthquakes. Such analysis lead us to the conclusion that the building was slightly damaged during the San Fernando earthquake, it was then retrofitted before Whittier, damaged again during Landers, and, finally, severely damaged during Northridge (De la Llera and Chopra, 1996). Using also the recorded accelerations, story shears and torques are computed by assuming the story masses of the building. Such results are presented in Fig. 2c, in which a point, denoted with "+", represents a combination of story shear and torque for a given instant of time. The interpretation of these plots has been studied earlier (De la Llera and Chopra, 1994). Finally, empirical story force-deformation relations are obtained by plotting story shears and story drifts, the latter computed from the integrated acceleration records.

BUILDING MODELS

The main objective of this phase was to estimate the uncertainty present in conventional linear building models used today in practice. For that purpose, a three dimensional finite element model was developed for each building, assuming rigid floor diaphragms and three degrees of freedom located at the center of mass (CM) of each floor, where all the story masses were lumped. A complete description of these models as well as the assumptions considered may be found elsewhere (De la Llera and Chopra, 1996).

Shown in Fig. 3 is a comparison between the predicted and "true" deformations at the roof of five of the buildings considered. It is apparent that the accuracy obtained between the predicted and actual responses is not good. The reasons for that vary from building to building. For instance, in building A, the nonlinear behavior of the structure, evidenced by the damage in the fourth-story columns, is not accounted for in the linear model developed. Note that the estimated traces of the roof deformation are similar to the true deformations during the first few seconds, but become substantially different after the building damages. Leaving aside building A, all other buildings remained elastic during this earthquake and one would expect a much better accuracy in their response predictions. However, as shown in the figure, the accuracy obtained by complex three dimensional linear models in terms of time responses as in peak responses is poor in general.

Although the sources of model uncertainty vary considerably among buildings, it is often true that in the case of linear elastic behavior of buildings, the structure of the model considered would be enough for a good fitting of predicted and "measured" responses if the parameters defining the model were varied. In other words, good predictions would be obtained if the model was adjusted a priori by identification of the building stiffness (principally) and mass properties.

IMPROVED ANALYSIS PROCEDURES

Because of the inaccurate responses predicted by linear models, a new simplified procedure for inelastic building analysis that has been recently proposed by the authors is evaluated and tested using recorded building responses. In this model, each story is represented by a single super-element (SEM) capable of representing the elastic and inelastic properties of the story. The formulation, accuracy, and implementation of this model are described in De la Llera and Chopra (1994). Presented next is the formulation and analysis of building A using a SEM model.

The first step in computing the SEM is to estimate the lateral and torsional capacities of each story. This is done by first computing the lateral capacity of each building column associated with a realistic axial load--assumed in this case equal to the gravity load--on it. Shown in Fig. 4a are the heightwise distribution of lateral capacities of the different columns of the building. In the figure, the values identified with circles and stars represent lateral capacities corresponding to shear and flexural failure mechanisms in each column, respectively. It is apparent that for essentially all columns shear failure mechanisms precede flexural mechanisms between the 2nd and 4th stories; these stories correspond to those most severely damaged during the earthquake.

Once the lateral capacity of columns is known, story shear and torque surfaces (SST) are constructed for each story using simplified rules (De la Llera and Chopra, 1994). Each point on one of these surfaces represents a static combination of story shear and torque that produces collapse of the story. Superimposed in Fig. 4b are the SST surfaces and the story shear and torque histories computed from recorded responses. Several interesting observations are obtained from Fig. 4b. First, it is apparent that all the response shear and torque combinations lie, as it should, inside or on the boundaries of the computed SST surfaces. Second, a close look of the third-story surface (Fig. 4c) shows that there is a number of story shear and torque combinations that approximately describe the SST, implying that the plasticity model implicit in the SST surface occurs in reality. Moreover, interpretation of the SST surface enables us to conclude that the building underwent inelastic torsional behavior in spite of its nominal symmetry---shear and torque combinations on the inclined branches correspond to predominantly torsional mechanisms. Indeed, it can be shown that this will be the case in most buildings with a perimeter frame as the only lateral resisting system.

Finally, by using the SST surface for each story, a SEM can be constructed to predict the inelastic response of the building. Such response is presented in Fig. 4d. Although differences still persist between model and "measured" responses, they are smaller than for the elastic prediction shown earlier in Fig. 3.

BUILDING ANALYSIS AND DESIGN IMPLICATIONS

This investigation has led to the following implications for building analysis and design:

A fundamental aspect in interpreting the building responses in this investigation was the use of recorded motions to the maximum possible extent without introducing strong modeling assumptions. Results based on tools such as story shear and torque histories help to establish inadequate inelastic properties of a building that otherwise would be hard to visualize. For the development and details of this and other useful record processing techniques the reader is referred to De la Llera and Chopra (1996).

The results presented earlier in Fig. 3 pose delicate questions such as: do we need to get as sophisticated as we do today using complex three dimensional linear building models in order to predict meaningful earthquake responses?, or why do our structural models "fail" in providing better predictions?.

In first place, buildings designed according to current codes, with large R factors, are likely to experience substantial inelastic behavior during a strong earthquake. For them, there is little hope that a linear model, as complete as it can be, will be able to predict representative earthquake responses. In that regard it would be better to use a simplified inelastic model, such as the SEM, capable of representing the fundamental inelastic features of the structure during the earthquake. In second place, the reason why our structural models fail in predicting more accurate responses is given through a counter example. Consider the response of base isolated buildings during the Northridge earthquake. Shown in Fig. 5 is a comparison between the predicted and "measured" deformations of the Fire Command and USC hospital buildings. Interestingly, the accuracy of these predictions is substantially better than that of fixed based buildings (Fig. 3). Why?, because the building behavior is controlled by elements with well known properties and behavior. Our sophisticated techniques of structural analysis are in this case extremely useful in providing realistic estimations. Indeed, to improve our earthquake response estimations we should improve our knowledge on the material and behavior of the structural elements used, or, otherwise, introduce in the design structural elements, such as dissipators or isolators, whose properties are well defined and in which the inelastic behavior of the structure is predominantly confined.

Finally, because several of the buildings considered are nominally symmetric, they are especially appropriate to evaluate the increase in response due to accidental torsion. This topic has been studied recently and design envelopes have been proposed to account for this effect (De la Llera and Chopra, 1994). The procedure proposed is based on a statistical study of the different sources of accidental torsion and avoids the cumbersome two extra analyses in each direction with shifted equivalent lateral forces or centers of mass. Shown in Fig. 6 are three design envelopes corresponding to values of $b/r=1,2$, and 3, where r is the radius of gyration of the building plan. Superimposed to these envelopes are the "recorded" increases in edge displacements due to accidental torsion in seven nominally symmetric buildings. First, as results insinuate, the increase in response of buildings with lateral to torsional frequency ratio, Ω, close to 1 is very sensitive to variations in Ω, as it has been predicted theoretically (De la Llera and Chopra, 1994). Moreover, it is apparent that buildings with larger Ω have a smaller increase in response due to accidental torsion as intended by the design envelopes. Because of this, it has been proposed that the effects of accidental torsion be neglected for buildings with $\Omega > 1.8$.

ACKNOWLEDGMENTS

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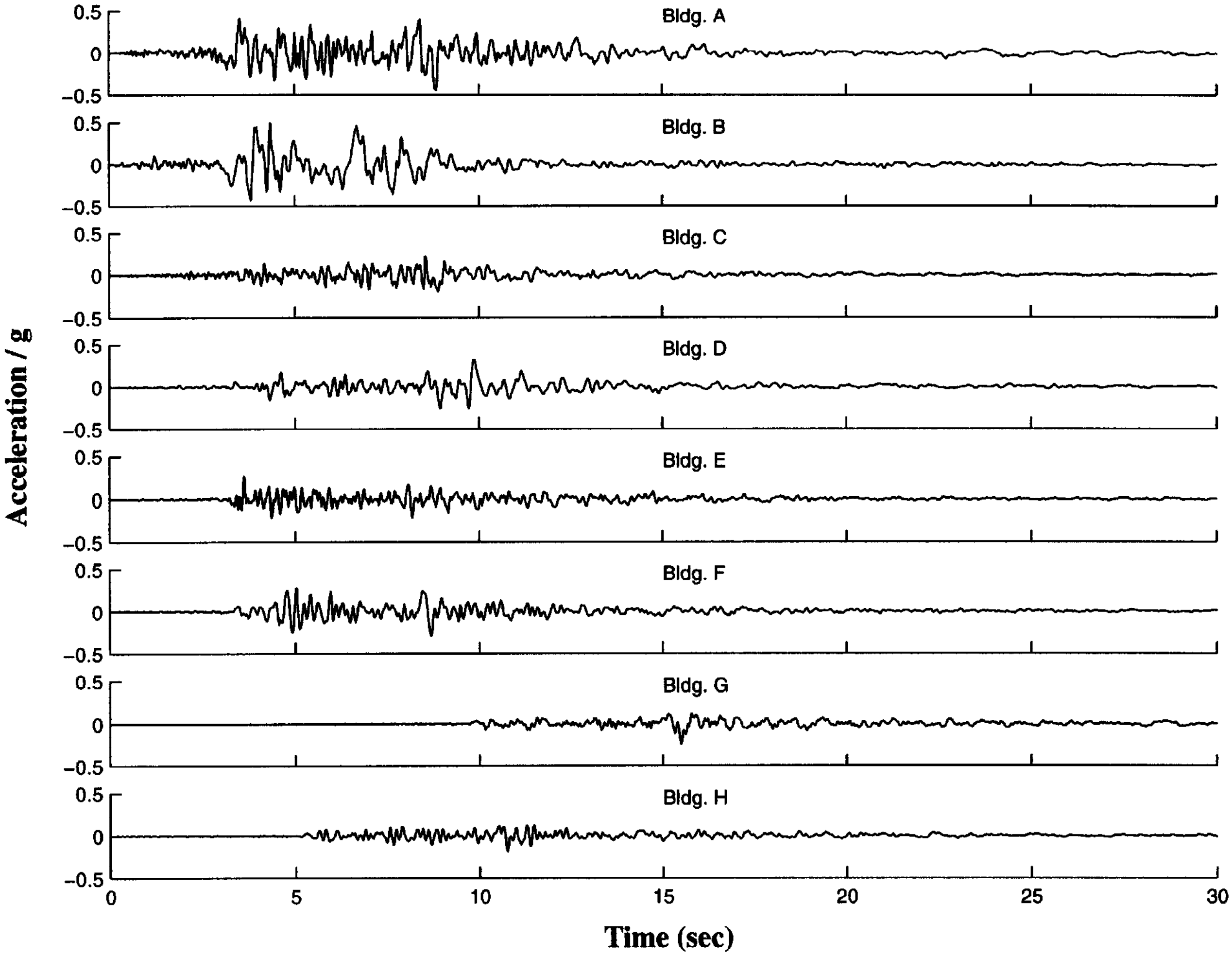

Figure 1: Recorded accelerations in all buildings considered in the East-West direction

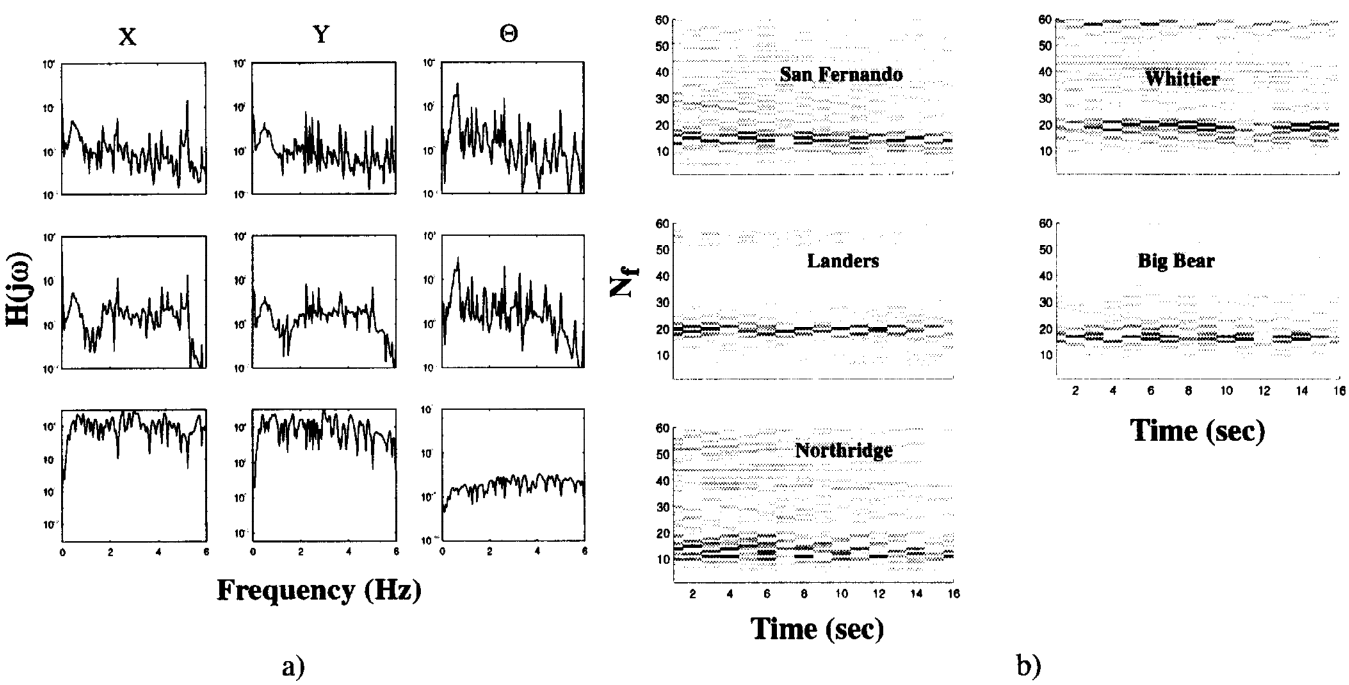

Figure 2: Selected results from record processing using building A as an example: (a) transfer functions at three building levels; (b) time frequency analysis; (cont.)

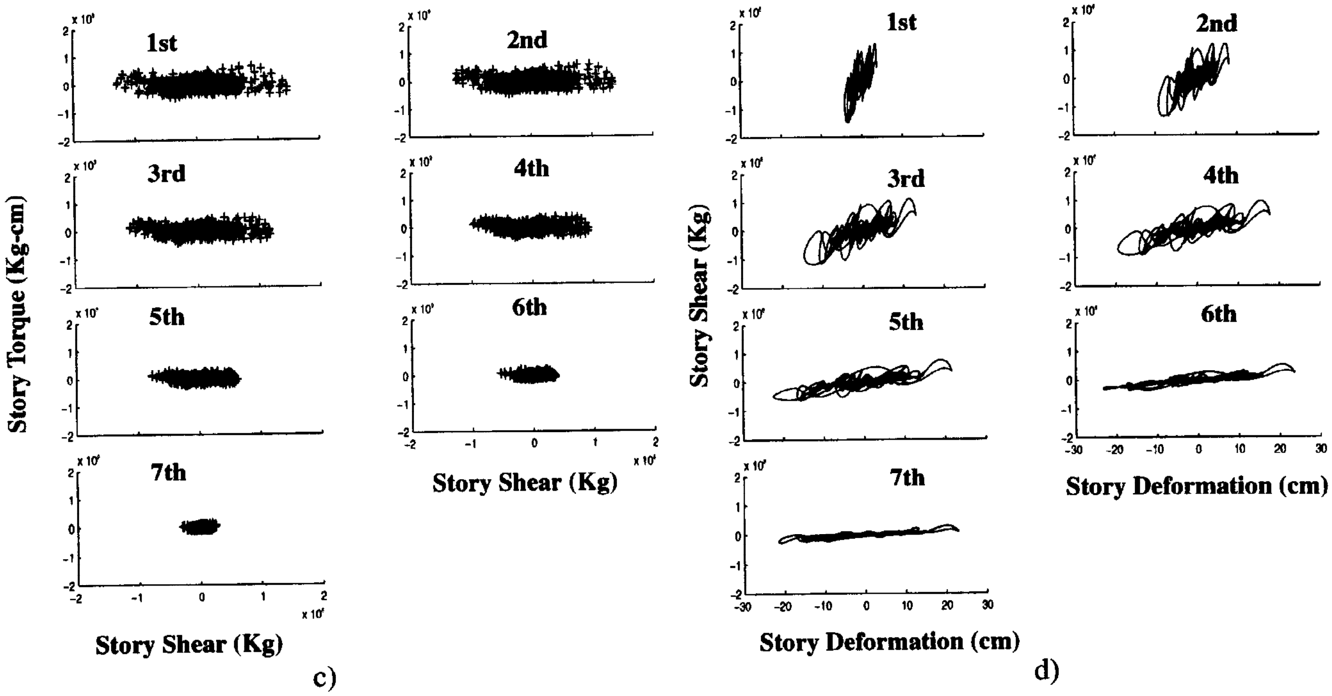

Figure 2 (cont.): c) story shears and torques; d) story shears versus story deformations

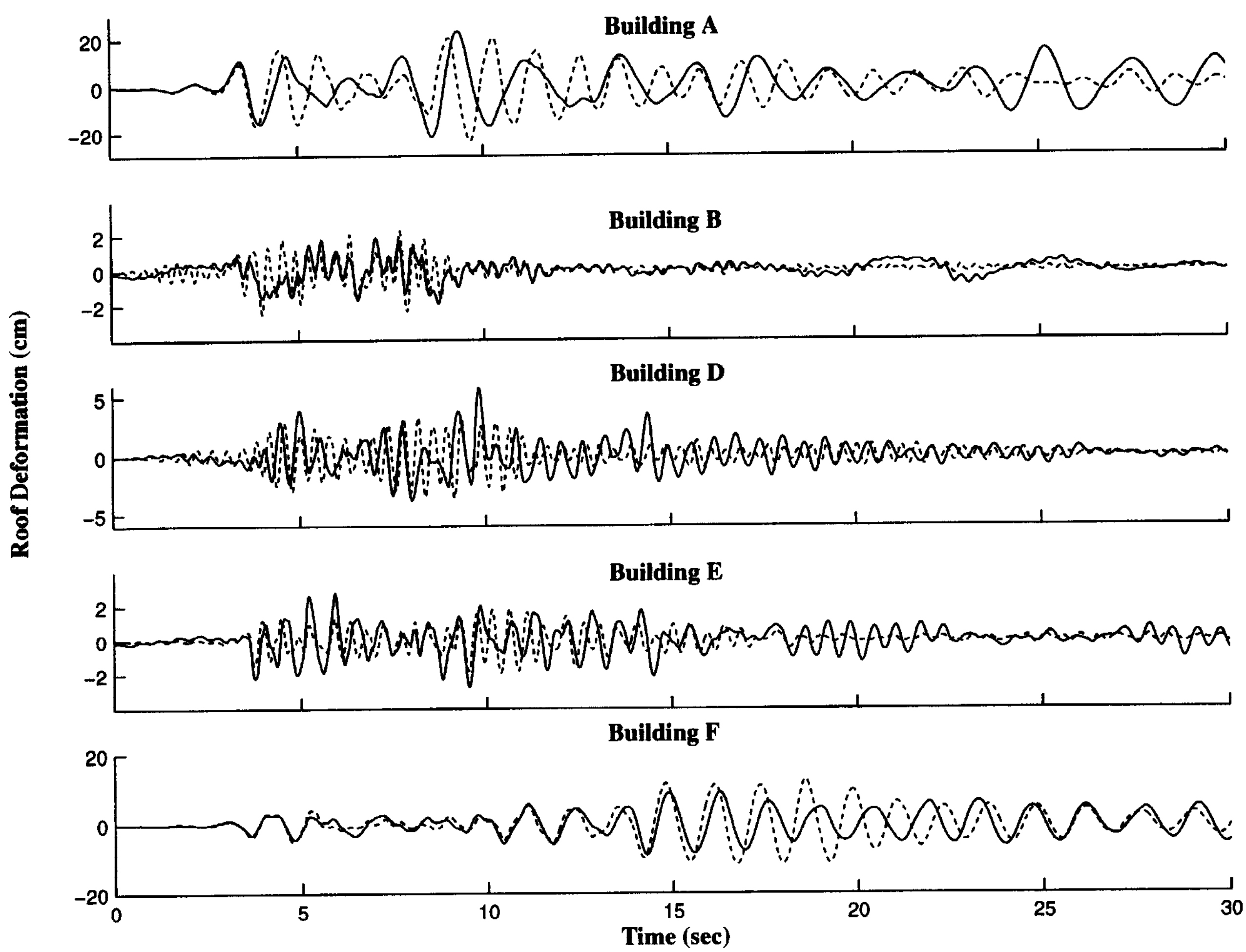

Figure 3: Comparison between predicted deformations at building roof using nominal linear elastic models (dashed line) and building deformations obtained from recorded motions (solid line)

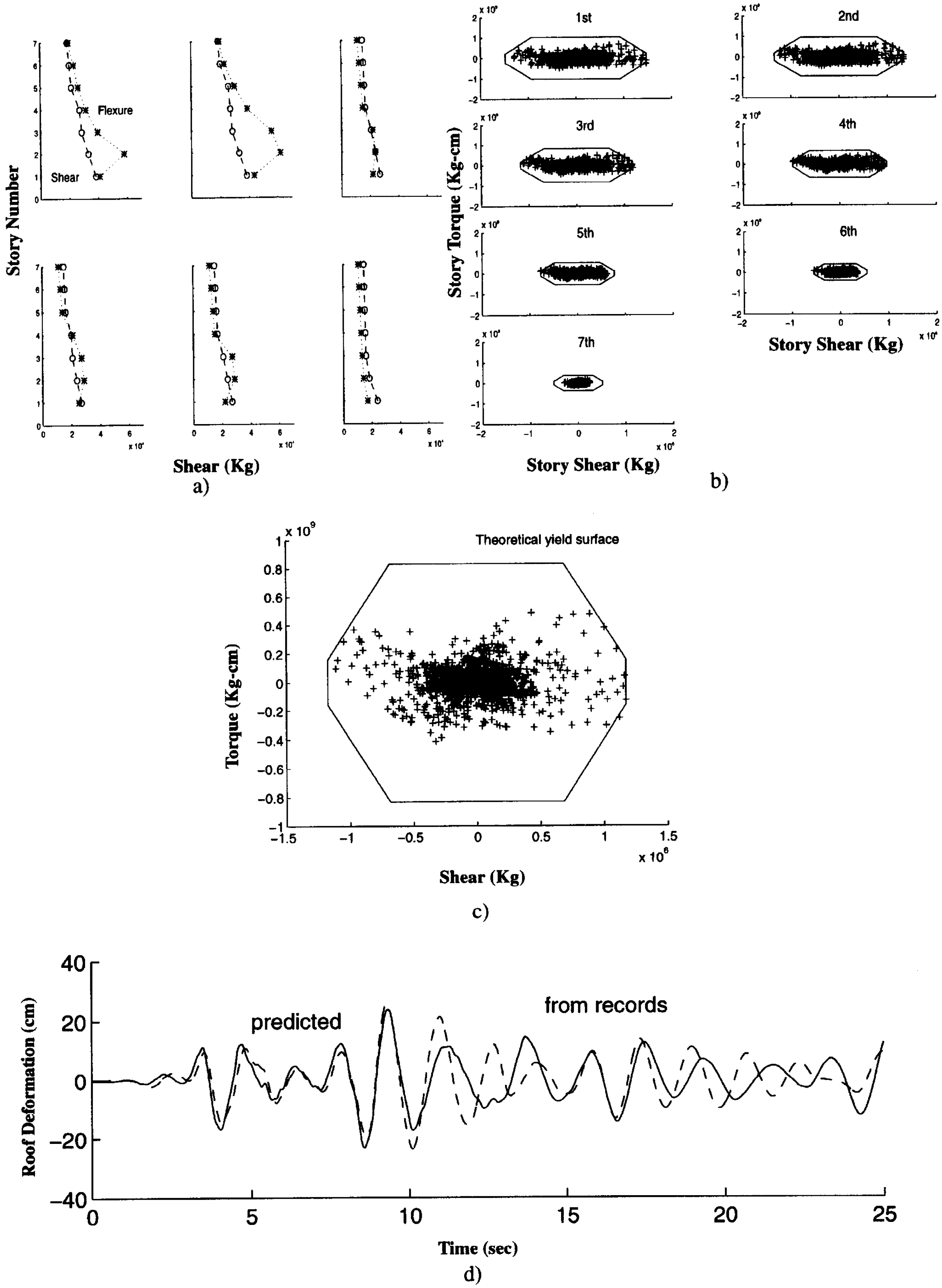

Figure 4: Inelastic analysis of Building A using a SEM model: a) shear capacities of columns; b) story shears and torques and ultimate surfaces; c) third story ultimate surface; and d) comparison between predicted building deformations and deformations computed from building records

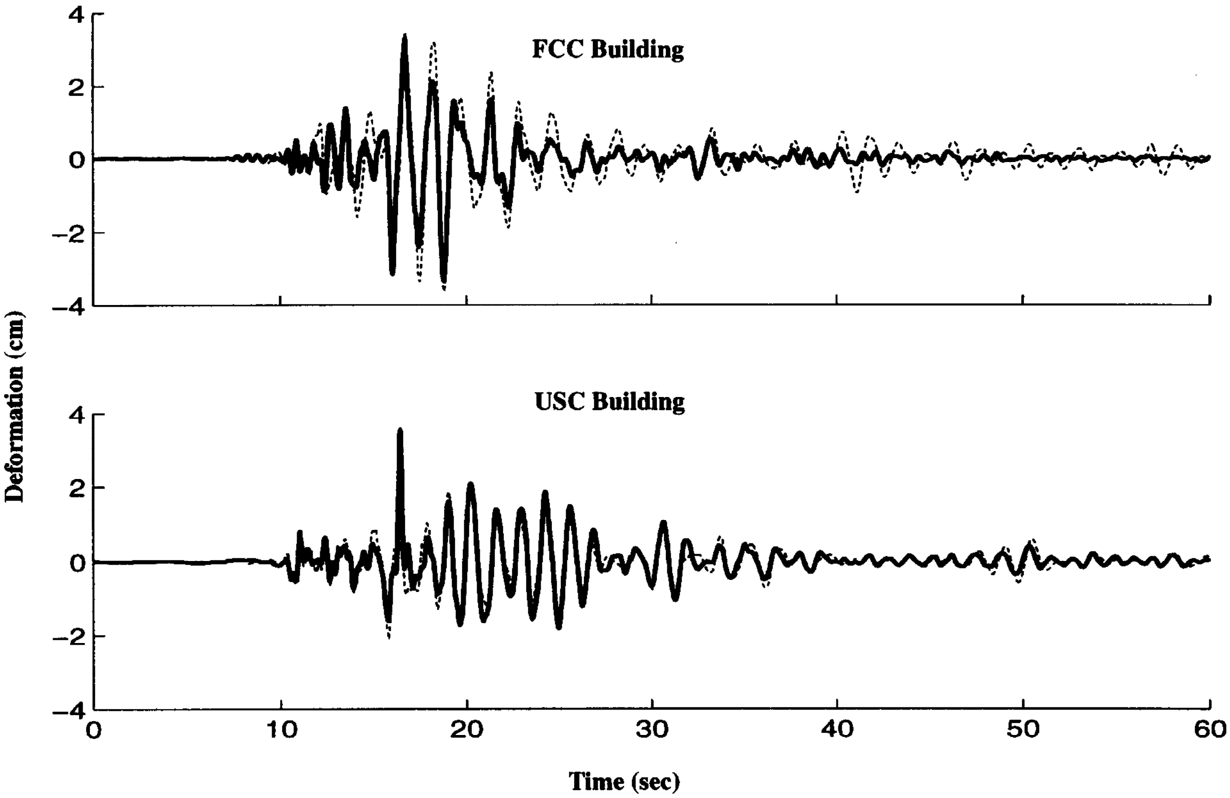

Figure 5: Comparison between predicted deformations on top of the isolators by an equivalent linear model and deformations obtained from recorded building motions

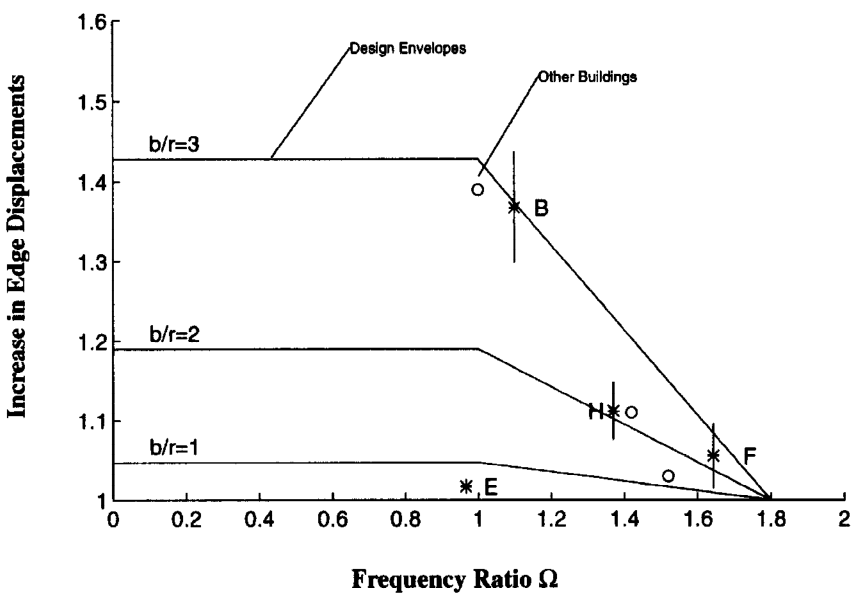

Figure 6: Comparison between design envelopes for the buildings selected and the 'true' increase in edge displacements due to accidental torsion computed from building records