LESSONS FROM STRUCTURAL DAMAGES OBSERVED IN RECENT EARTHQUAKES

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SUMMARY

After reviewing present knowledge in seismic-resistant building construction, the objectives of a research program on post-earthquake damage inspection and analysis are presented. Results and observations of investigations of several buildings in four different earthquakes are summarized. The lessons learned from these investigations reiterate both the importance of proper selection of building layout, of recognizing possible interacting effects of nonstructural components with the structure, and of detailing and workmanship, and the limitations of present analytical methods of estimating demands.

INTRODUCTION

Introductory Remarks. The last few decades have witnessed many advances in the field of earthquake engineering; however, many researchers and most professionals working in this field feel that the design and construction of earthquake-resistant structures is still an art and not a science [1-3]. One critical ingredient in such design and construction is seasoned engineering judgment; the best way to develop such judgment is by field surveys of the performance of actual structures during earthquakes and in-depth analyses of the damages observed. These observations and analyses provide invaluable evidence concerning the effectiveness of seismic codes and procedures used in design and of available analytical methods.

In view of the importance of studying the performance of structures during earthquakes, a research program based on post-earthquake damage inspection and analysis was started in Berkeley several years ago [4-13]. The specific objectives of this program are (1) to identify the reasons for the observed damage, and in this way to assess the reliability of various analytical models and techniques for predicting structural response to earthquake ground motions; (2) to assess possible improvements in design and construction practice which might minimize the observed types of damage in future earthquakes; (3) to investigate ways of strengthening, stiffening, toughening, and/or modifying existing structures to minimize the danger of significant damage during future earthquakes; and (4) to assess the efficiency of present methods of repairing structures damaged during earthquakes and to search for more efficient methods. A summary of some of the results obtained in this program is presented herein.

Objectives. The main purposes of this paper are (1) to review the different factors that can affect the seismic behavior of buildings; (2) to summarize the reasons for damages observed in several buildings during recent earthquakes; and (3) to develop lessons from these observed damages and to assess their implications with respect to present methods of design, analysis, construction and maintenance of earthquake-resistant buildings.

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FACTORS CONTROLLING EFFICIENCY OF SEISMIC-RESISTANT CONSTRUCTION

General Factors. In-depth studies of the performance of buildings during recent damaging earthquakes [4-13] point out that efficient seismic-resistant construction necessitates careful attention to the total seismic design, construction, and maintenance process. The phases of this process include: evaluating the seismic threat, selecting the structural layout, predicting the mechanical behavior of the whole soil-building system, proportioning and detailing the structural components with their connections and supports, analyzing the reliability of the design obtained, and constructing and maintaining the building during its service life [1-3].

The inelastic response of a building is extremely sensitive to its initial dynamic characteristics, and those of the ground motion, and to the hysteretic behavior of its nonstructural and structural components, which depends on their detailing. This sensitivity is shown in studies of the response of concrete structures to severe earthquakes, and must be recognized to properly interpret results which will be presented later. Performance of a structure depends on its state when the earthquake strikes, which may differ significantly from the state the designer envisioned. Thus, construction and maintenance, which includes modification and repair, must also be considered in addition to general design aspects. The importance of these factors is illustrated by results obtained in the following studies.

STUDIES OF SEISMIC PERFORMANCE OF BUILDINGS

1972 Managua, Nicaragua, Earthquake. Two reinforced concrete buildings, the 15-story Banco Central and the 18-story Banco de America, were located on adjacent sites in Managua at the time of the earthquake (Fig. 1). Due to extensive earthquake damage, the top 12 stories of the Banco Central were demolished. However, only moderate structural repairs were required in the Banco de America. To determine the reasons for this difference in performance, a number of detailed dynamic analyses were performed [7,11,12]. Accelerograms from the Esso Refinery, about 5 km from the buildings, were used in these analyses.

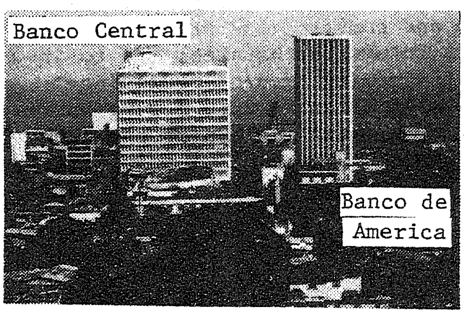
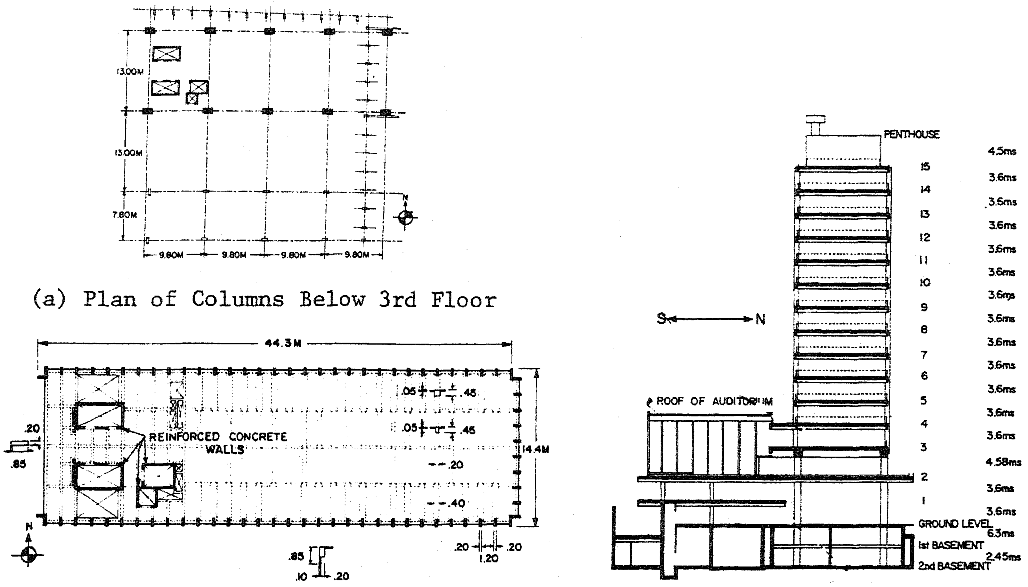


FIG. 1. VIEW OF BANCO CENTRAL AND BANCO DE AMERICA, MANAGUA

Banco Central [11]. The configuration and structural system used for the Banco Central were complex (Fig. 2). In the upper portions of the tower, the floor system consisted of a 0.05 m slab supported by 14 m-long joints having a total depth of only 0.45 m. Closely spaced columns located along the north, east and south sides of the tower were replaced by ten 1 x 1.55 m columns below the third floor. In the bottom two stories, waffle slabs were used to extend the plan of the building considerably to the south. Four elevator shafts, enclosed by reinforced concrete walls, were eccentrically located in the west end of the tower.

The perimeter columns between the fourth and fifteenth story suffered extensive cracking. The walls around the elevator shafts suffered cracking and spalling of the concrete and buckling of the reinforcement in the fourth and fifth stories. Transverse cracks, sometimes wider than 10 mm, were observed



(a) Plan of Columns Below 3rd Floor

(b) Typical Plan of Upper Stories

(c) Elevation

FIG. 2. PLANS AND ELEVATION OF BANCO CENTRAL

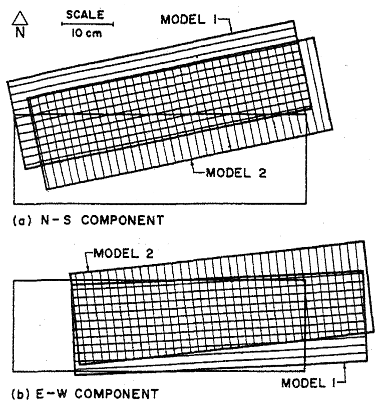
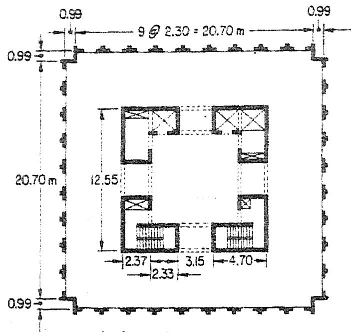


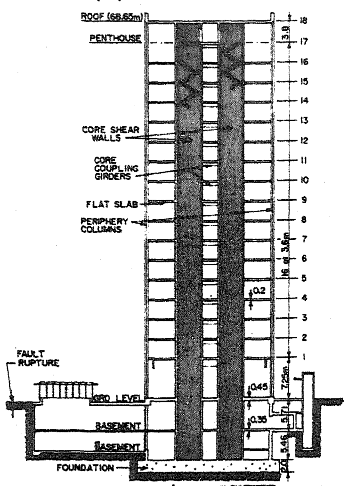
FIG. 3. ROOF DISPLACEMENT OF BANCO CENTRAL FOR ESSO REFINERY RECORDS

across all slabs above the third floor just to the east of the elevator shafts. Hollow clay tile infilled walls (located on the west face of the tower, beneath the windows on the other faces of the tower and around the stairwells) and other nonstructural elements suffered substantial damage.

Three elastic analytical models were considered. Model 1 was three-dimensional and included all structural elements as well as the hollow clay tile infilled walls. Model 2 was similar but the nonstructural elements were disregarded. In Model 3, inertial forces resulting from horizontal and/or vertical ground excitations, on a representative transverse frame, could be accounted for. Based on the results of these elastic analyses, the following observations can be made: (1) the substantial change in structural configuration as well as the eccentric location of the elevator shaft walls resulted in substantial torsional response (Fig. 3); (2) the tile partitions lowered the fundamental period about 20% and significantly modified the response (Fig. 3); however, computed elastic forces in these members far exceeded their capacities and they would begin to fail very early in the response; (3) the shear capacity of most columns along the north and south sides of the tower above the third floor would be exceeded assuming peak EW ground accelerations only 40% of those recorded at the Esso refinery; (4) due to the relative stiffnesses of the remaining uncracked members, any additional inertial forces developed in the eastern portion of the tower were transferred primarily back



(a) Plan



(b) Elevation

FIG. 4. PLAN AND ELEVATION OF BANCO DE AMERICA

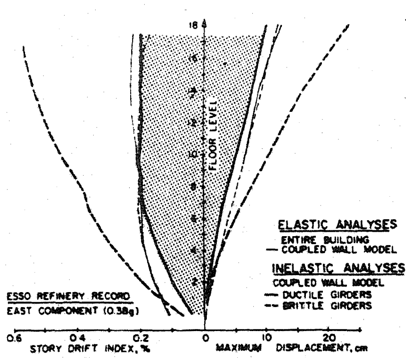


FIG. 5. ENVELOPES OF MAXIMUM FLOOR DISPLACEMENTS AND STORY DRIFTS--BANCO DE AMERICA

to the elevator shaft walls by means of in-plane diaphragm forces resulting in transverse slab cracks and damage to the elevator shaft walls; (5) even for horizontal excitations, the long, flexible floor joists developed significant vertical motion contributing substantially to the damage in the nonstructural elements they supported.

Banco de America [7,12]. As indicated in Fig. 4, the structural system of the Banco de America is essentially symmetric. The primary lateral force resisting system consisted of four large L-shaped wall cores, symmetrically coupled by pairs of girders. Because of duct openings placed at the center of the coupling girders, their shear capacities were generally only about 35% of the values required to develop their flexural capacities. Shear failures in these girders were the primary structural damage observed in the building. Elastic three-dimensional analyses of the whole building and inelastic two-dimensional analyses of the coupled wall system indicate that (1) the symmetric structural configuration and relatively stiff and strong coupled wall system effectively limited displacements and drifts (Fig. 5) and prevented any significant torsional influence; (2) avoidance of long floor spans and masonry partitions reduced nonstructural damage; and (3) when coupling girder shear failures were accounted for, displacements significantly increased (Fig. 5) but were limited due to the considerable remaining lateral stiffness and strength provided by the walls.

1976 Guatemalan Earthquake [9]. During this earthquake a relatively modern three-story reinforced concrete building, La Escuela De Niñeras (Nursery School) (Fig. 6), which utilized structural frames infilled with masonry, suffered seismic damage characteristic of this type of frame-infill construction, i.e., "captive column" failures due to infill panel restraint, "explosive" shear failures of infill panels, and masonry debris blocking exits and stairways (Fig. 7).

The post-earthquake study of this building reviewed its construction and its seismic behavior and investigated its dynamic character through a series of linear elastic studies. The structural contribution of the infill to the frame was modeled analytically by a constraint approach [13] and the influence of the infill upon the structural response to different earthquake excitations, including the 1976 Guatemalan record, was considered in detail. These analytical studies indicated that the infill had the effect of shortening the natural periods of the building, tuning the structure to a

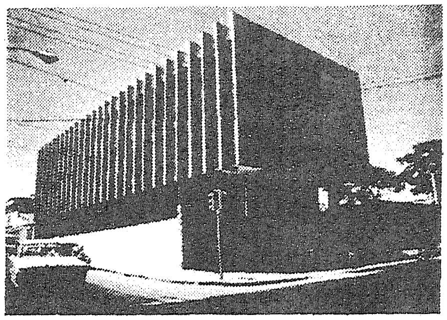


FIG. 6. VIEW OF ESCUELA DE NIÑERAS

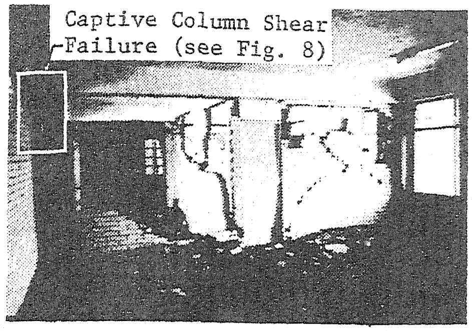


FIG. 7. WALL DAMAGE AT TRANSVERSE FRAME

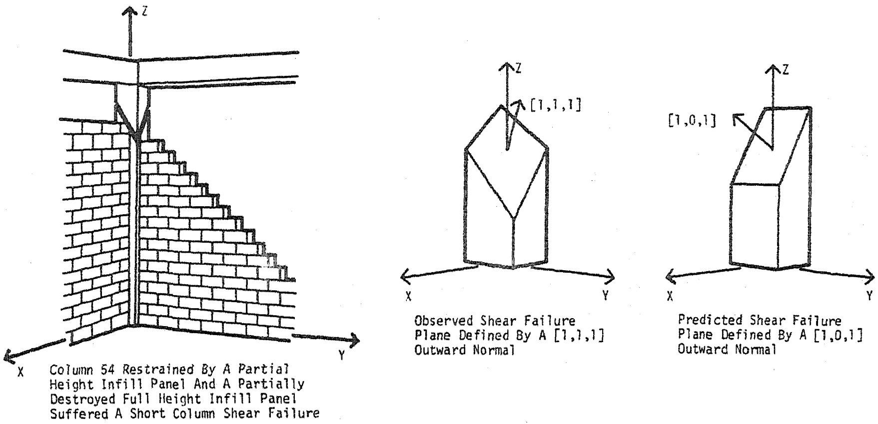


FIG. 8. DETAIL OF THE SHEAR FAILURE OF THE CAPTIVE COLUMN 54

dominant frequency content of the Guatemalan record. The highly irregular and asymmetric distribution of infills in the otherwise relatively regular and symmetric frame introduced significant torsional response and thus a concentration of (computed) stress in two of the seven transverse frames that correlated well with the observed damage. The constraint approach provided a sufficiently detailed estimation of member forces and local infill stresses to indicate the probable nature of failure of a critically damaged column (Fig. 8), insofar as the brittle nature of the building response allowed realistic modeling elastically. Furthermore, the combined evidence of the observed damage and analytically predicted behavior (1) suggested one probable failure mechanism for completely infilled frames, and (2) demonstrated a positive correlation between observed infill damage levels and predicted infill stress levels, encouraging consideration of a damage limit state based upon a parameter of infill stress (or strain) rather than drift.

<u>1977 Caucete (San Juan, Argentina) Earthquake</u> [10]. Regarding the performance of structures, the main features of this earthquake were (1) the poor behavior of cylindrical liquid storage tanks; (2) the excellent behavior of one- to three-story dwellings constructed (according to code regulations developed after the destructive earthquake of 1944) using masonry properly restrained by R/C beams and columns; and (3) the relatively poor performance of some school buildings due to poor construction, poor selection of building layout, and, in some cases, due to a disregard for the interaction of nonstructural elements

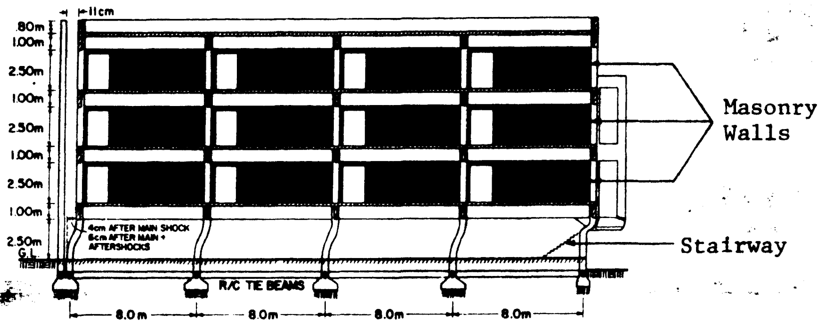


FIG. 9. LONGITUDINAL ELEVATION OF THE ENET NO. 2 BUILDING ILLUSTRATING PERMANENT DISPLACEMENT AFTER EARTHQUAKE

with the structure. A good illustration of this poor performance was that of the Escuela (School) ENET No. 2. This building consisted of a four-story R/C moment-resisting space frame. The first story was left completely open in the longitudinal direction, while the frames in the upper three stories were infilled with masonry walls to provide several classrooms (Fig. 9). These decisions and resulting construction led to a soft first-story building type response to the earthquake. The first-story columns underwent significant inelastic deformations resulting in a permanent horizontal displacement of 40 mm after the main shock and increasing to 60 mm due to aftershocks. Three-dimensional linear elastic analyses were performed assuming different models (neglecting and including nonstructural elements) and using the earthquake ground motion recorded 2 km from the building. Nonlinear dynamic analyses were also conducted. The above analyses lead to the following observations: (1) the linear elastic analyses show the significant effect of the masonry walls located in the upper stories, which not only increased the overall stiffness of the building but, more importantly, significantly changed the modes of vibration, practically converting it to a soft first-story building; (2) the columns of the first story exceeded their "elastic" range; (3) the nonlinear analysis predicted a permanent deformation of 38 mm which is very close to the measured 40 mm; and (4) the columns as designed and constructed were just capable of developing the ductility required which was about 2.5.

1979 Imperial Valley (California) Earthquake. As far as performance of structures is concerned, the main features of this earthquake were (1) significant damage to cylindrical liquid storage tanks, either ground supported or elevated, and (2) the recorded performance of the modern six-story Imperial County Services Building in El Centro (Fig. 10). Thirteen accelerograms recorded the motion at various locations in the building, which suffered significant structural damage. This six-story building is rectangular in plan (23 x 42 m). Lateral resistance is provided by moment-resisting frames in the longitudinal direction (EW), and shear walls were used in the transverse direction (NS). Shear walls in the upper five stories were provided for the full width of the building on its east and west faces. Four considerably narrower shear walls were asymmetrically placed in the first story. Damage to the building consisted of the failure of the four columns along the east side at the ground level (Fig. 11), spalling of concrete cover and buckling of longitudinal steel in other columns at the ground level, and cracking in slabs, beams, columns, and shear walls throughout the building. A detailed field survey of the damages and preliminary study of the design and detailing indicate that the observed failure of the columns was due to a combination of factors: (1) discontinuities in the

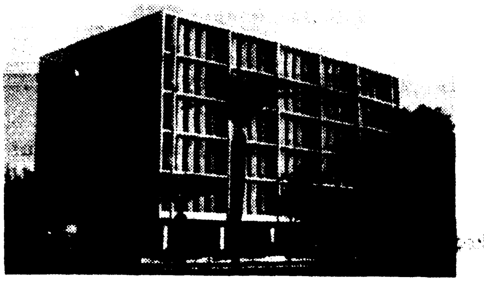


FIG. 10. VIEW OF THE IMPERIAL COUNTY SERVICES (ICS) BUILDING, EL CENTRO, CALIFORNIA

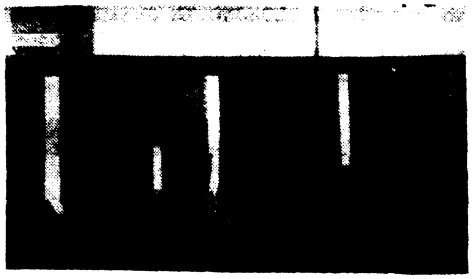


FIG. 11. FAILURE OF THE FOUR GROUND-STORY COLUMNS LOCATED AT THE EAST SIDE OF BUILDING OF FIG. 10

structural system at the second-floor level; (2) interruption of the special lateral reinforcement at the "created" critical regions near the lower end of the columns; and (3) bending of the column main reinforcement at these critical regions.

LESSONS LEARNED

Based on the performance and analyses of the buildings studied, the following lessons regarding seismic-resistant design and construction were learned: (1) Proper selection of structural layout and systems is essential. Compact symmetrical layouts and the avoidance of discontinuities in mass, stiffness, strength and/or ductility are crucial. Multiple lines of defense are desirable; (2) Flexible long span floor systems can result in large horizontal and vertical displacements which can contribute to nonstructural damage; (3) Failure of nonstructural components can result in serious threat to life and contribute significantly to the cost of repair; (4) Nonstructural infill elements often have a primary effect on seismic response and should be considered in design or adequately isolated. If ignored in design, such infills can lead to unanticipated, and potentially catastrophic, modes of structural behavior; (5) Members and connections should be detailed and constructed to have a large ductility capacity due to the uncertainty in ductility demands; (6) Analytical studies should include the effects of vertical inertial forces and of nonstructural components where appropriate. Inelastic analyses are needed to estimate ductility demands.

Conclusions. These lessons clearly indicate that at present, because of large uncertainties in estimating the demands in earthquake-resistant design of buildings, it is of paramount importance to pay more attention to "conceptual" than to "numerical" design. Sophistication in selection of building layout (structural system, structural material, nonstructural components) is at present more important than sophistication in estimating demands (analysis). The inertial forces depend upon the interacting effects of the ground motions with the mass, damping, and structural characteristics of the building. Therefore, designers need to understand how design and construction decisions may create serious seismic effects. Guidelines for selecting a proper structural layout are discussed in Refs. 2, 3 and 14.

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