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Behaviour Assessment of Rehabilitated Buildings in Mexico City

Evaluation du comportement de bâtiments réparés à Mexico

Bewertung des Verhaltens wiederhergestellter Gebäude in Mexico City

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SUMMARY

After the earthquakes of 1985, over 1000 structures were rehabilitated in Mexico City. Due to the lack of technical guides available worldwide at that time, design and construction of retrofits were based on engineering judgement, intuition and experience. Different approaches were followed for solving similar problems; different degrees of safety were incorporated in analysis and design. A long-term research program is underway to assess the analysis, design, and construction considerations by studying the performance of rehabilitation schemes under future moderate and severe ground motions. Trends on the use of rehabilitation techniques for different types of structural systems have been identified.

RÉSUMÉ

A la suite des tremblements de terre de 1985, plus de mille immeubles ont été réparés à Mexico. Ne disposant à cette époque d'aucune règle technique dans le monde entier, la conception et la construction des réparations et le renforcement ont été réalisés sur la base de l'intuition et l'expérience des ingénieurs. Différentes approches ont été utilisées pour résoudre des cas similaires; différents facteurs de sécurité ont été incorporés dans la conception. Afin d'évaluer les hypothèses retenues dans le calcul, la conception et la réparation des bâtiments, un programme de recherche à long terme a été développé, en vue d'étudier le comportement des alternatives de réparation sous sollicitations de séismes, modérés et intenses. Certaines tendances apparaissent sur l'emploi des techniques de réparation pour différents type de systèmes structuraux.

ZUSAMMENFASSUNG

Seit dem Erdbeben von 1985 wurden mehr als 1000 Gebäude wiederhergestellt. Wegen der weltweiten Knappheit technischer Fachleute, basieren die Reparaturen auf Meinungen, Intuitionen und Erfahrungen von Ingenieuren. Unterschiedliche Ansätze wurden für ähnliche Probleme verwendet; unterschiedliche Sicherheitsfaktoren wurden gebraucht. Ein langfristiges Forschungsprogramm zur Bewertung der Berechnung, des Entwurfs und der Konstruktion von wiederhergestellten Gebäuden wird entwickelt. Tendenzen von Wiederherstellungstechniken wurden festgestellt.

1. BUILDING BEHAVIOR DURING THE 1985 MEXICO EARTHQUAKE

On September 19, 1985, an 8.1 magnitude earthquake struck the nation's capital city. Although the focus was 400 km WSW from the city, the uniqueness of the ground motion intensity, frequency content, duration, and regularity was manifest in Mexico City. From the total building inventory of the city, only 1.4% collapsed or sustained serious damage. Most damaged and collapsed buildings were reinforced concrete (RC) frames and waffle slab structures, which proved the most vulnerable of all types of structures. An statistical summary of damage to buildings can be found elsewhere [1]. Cases of collapse or serious damage were mostly limited to buildings more than four stories tall. The most vulnerable proved to be those having 7 to 15 stories. The relationship between number of stories and vulnerability was explained in terms of the spectral shapes and the buildings' fundamental period of vibration.

For steel structures, primary causes of damage were local buckling or fracture of open-web members, local failure of box section columns, and inelastic buckling of slender cross bracing of old (pre-1957) structures [2]. In RC frame structures, the damage generally involved column failures due to high axial and flexural forces, shear failure in short captive columns, shear distress in beams due to large lateral movement or settlement of foundations, and joint distress due to inadequate confinement or poor layout of connected members. In RC slab structures, damage frequently was associated to shear distress near the column or at the edge of the "capital" over the column, punching shear, which probably initiated collapse of a number of floor slab structures, and flexural distress in columns.

Of the buildings that suffered collapse or severe damage, 42 percent were corner buildings. Most of these had masonry walls on two perpendicular sides and wide open facades to the street. In some cases, torsion was due to asymmetric layout of masonry filler walls. Weak first story failures were also due to an irregular distribution of masonry filler walls along the height, thus leaving the frames in the ground floor practically bare.

2. TYPICAL REHABILITATION SCHEMES USED IN MEXICO CITY

Over 1 000 buildings were rehabilitated after the September 1985 earthquake. Repair and strengthening of structures began almost immediately. Owners of damaged buildings were anxious to restore operations in their structures. A substantial number of buildings which suffered little or no damage were strengthened. In many cases strengthening was undertaken because similar buildings had collapsed or were heavily damaged. All repair and strengthening design had to meet the emergency building regulations (in effect until 1987), and since then, the current Mexico City Building Code [3]. Both demanded higher lateral forces and more stringent requirements to attain ductile behavior. Design requirements for rehabilitation of buildings were the same as those for new construction. Rehabilitated structures included schools and hospitals. The seismic safety of over 4 795 schools and 216 hospitals has been assessed. From the 1 687 schools affected by the earthquake, 1 658 structures with different levels of damage were repaired [4].

Techniques used for retrofitting were intended to both strengthen and stiffen the structures. In most cases, economic factors dictated the direction taking in rehabilitating the structure. However, least cost for construction was not always the most important consideration in selecting a rehabilitation technique. Many existing damaged and undamaged structures were rehabilitated at costs which would have exceeded demolition and reconstruction costs. This was done to preserve the amount of space that could be leased at premium rates because ordinances enacted since the structure was originally built would have required the inclusion of parking for occupants or a change in the use of the site.

The predominant rehabilitation techniques were column jacketing, addition of shear walls or diagonal bracing (designed to carry all or most of the lateral force), replacement of damaged elements, and removal of top floors. Relative merits and limitations of the techniques used have been discussed elsewhere [5]. At the time of the rehabilitation works, only qualitative design guidelines were available so that a great deal of engineering judgement and intuition were involved in the decisions regarding rehabilitation and severity of damage. Since then, several techniques have been assessed experimentally to provide a scientific basis for making such decisions [6,7].

3. RESEARCH PROGRAM

The National Center for Disaster Prevention (CENAPRED) in Mexico City has launched a long-term research program aimed at studying the behavior of rehabilitated buildings in the city, and at assessing the adequacy of the analysis, design, and construction considerations made for retrofitting. Monitoring the response of rehabilitated buildings in future ground motions will be carried out as part of this program. The project underway has been divided into four phases.

Phase I - Database of rehabilitated buildings. A database of some rehabilitated buildings in Mexico City was developed. To obtain relevant data from rehabilitated buildings a two-page questionnaire was prepared [8]. This questionnaire was sent to 15 design offices which have been involved in building rehabilitation in Mexico City. Collaboration of consulting firms was voluntary. Confidentiality of the information was warranted.

Phase II - Selection of typical buildings. From the buildings included in the database, a dozen structures are being selected based on a simple and symmetrical structural layout, typical rehabilitation scheme, availability of structural drawings, and importance of the structure. A complete record for each building will be prepared. Original structural drawings, damage information, and structural drawings of the rehabilitation will be included. At present two buildings, a school and a hospital have been selected.

Phase III - Assessment of selected buildings. Safety levels of selected buildings will be assessed by standard evaluation procedures. A first-level evaluation will be based on a visual inspection of the building for identifying characteristics that might be associated to substandard earthquake behavior. Items to be checked are the layout of structural system (both in plan and elevation), foundation characteristics, location, and damage. In a second-level assessment, a seismic safety index, based on cross-sectional areas of supporting (vertical) elements, will be compared to an intensity index, which reflects the seismic hazard of the zone where the building is located. In the third-level evaluation, the seismic capacity will be determined on the basis of current code provisions, and on state-of-the-art knowledge of behavior. Linear elastic and nonlinear analysis will be performed. An evaluation strategy for each selected structure will be developed so that it would be applied after future earthquakes. Ambient vibration tests will be performed to obtain the dynamic characteristics of buildings.

Phase IV - Post-seismic evaluation of selected buildings. At the occurrence of a moderate or severe ground motion, selected buildings will be inspected and evaluated. The performance of the rehabilitation schemes will be studied. Results from Phase III will be assessed in light of the responses observed. Two buildings will be instrumented with acceleration and displacement transducers.

4. PHASE I - DATABASE OF REHABILITATED BUILDINGS

Gathering of information has been a lengthy process. Since the cooperation of design firms has been voluntary, the time required to complete this phase has been dictated by the availability of consulting engineers. At present, 196 questionnaires have been received. Most structures (89%)

Activity	No. of Buildings	Percentage
Hospitals	16	9
Schools	138	81
Phone Stations	7	4
Mail Buildings	2	1
Offices	9	5

Table 1 Classification of Group A buildings

are located in the lake bed zone, characterized by soft clays, which is the area that showed the largest ground motion amplifications during the 1985 earthquake. The majority of the buildings are in zone most hardest hit by the earthquake.

Most buildings in the database are Group A structures (Table 1), which are defined by [3] as those which must be serviceable after an emergency and those in which large crowds may gather. In Table 2 building statistics based on type of vertical system are shown. Consistent with the damage observed in 1985, non-ductile RC frames (characterized by strong beam - weak column systems, wide tie spacing, flexible columns) and waffle slab structures are predominant. Schools are included in the non-ductile RC frame category.

Type of Vertical System	Frequency
1. Steel Frames	
a. Unbraced	13
b. Steel braces	1
c. RC walls	0
d. RC infills	0
e. Masonry infills	1
2. RC Frames	
a. Ductile detailing	1
b. Non-ductile details	140
c. RC walls	5
d. Masonry walls	13
e. Precast frame members	0
3. Masonry	
a. Reinforced	3
b. Confined	4
4. Waffle slab structures	
a. Without walls	34
b. With walls	4
5. Others	1

Table 2 Vertical system of sampled buildings

Regarding the floor system, 120 buildings have cast-in-place concrete slabs with beams. Most buildings have shallow foundations (164), which correspond to low-rise schools and clinics up to four stories high. As for deep foundations, 11 buildings are supported on bearing piles, while 21 are on friction piles.

The number of structures rehabilitated by the different types of rehabilitation techniques is shown in Table 3. It is clear that the techniques most widely used were those that strengthened and stiffened the structures. Jacketing of frame members, either with concrete or steel, and bracing of the building (with RC walls or steel rolled shapes) are predominant. A large number of structures in our sample were retrofitted with prestressing cable braces; this was the case of almost all schools and some low-rise hospitals.

Analysis of the information has shown that for RC frames with non-ductile detailing, jacketing of members was the technique most widely used (52 cases). In 11 of the 52 buildings, RC walls were added besides jacketing. Similar conclusions were reached for waffle slab structures.

Further assessment of the information indicates that in 85% of the cases, rehabilitation was performed to upgrade the structural characteristics to present code requirements although the structures were undamaged; this is closely related to the large number of group A structures in the

Type of Rehabilitation Technique	Frequency
1. Epoxy resin injection	17
2. Replacement of buckled reinforcement	6
3. Concrete jacketing	
a. Columns	15
b. Beams	0
c. Both	23
d. Joints	11
4. Steel jacketing	
a. Columns	13
b. Beams	0
c. Both	7
d. Joints	3
5. Addition of RC walls	33
6. Addition of RC infills	0
7. Addition of steel braces (rolled shapes)	25
8. Macroframes	6
9. Mortar cover reinforced with WWF mesh	11
10. Prestressing cables	128
11. Strengthening of floor diaphragm	0
12. Strengthening of wall-to-slab connection	9
13. Addition of piles	9
14. Jacketing of grade beams	14

Table 3 Statistics of the rehabilitation techniques used

sample (88%), which are required to fulfill the code [3]. Twenty-nine structures were retrofitted because they were damaged during the earthquake; it is important to point out that damaged structures were repaired soon after the event. Files for those buildings were not easily accessible in design firms; the majority of the structures sampled was rehabilitated after 1987.

The Mexico City Building Code accepts a reduction of the elastic design forces (elastic design response spectrum) based on inelastic behavior (ductility and energy dissipation) with a maximum response factor Q equal to 4. Q factors are 4, 3, 2, 1.5, and 1. As it is common, the largest the Q-factor, the more stringent are the reinforcing detailing requirements to attain ductile behavior. Detailing for Q=4 in RC structures is similar to that embodied in Chapter 21 of ACI- 318 code [9]. The vast majority of structures was designed for seismic effects using a response factor Q equal to 2. In this sample, Q factors equal to 3 and 4 were used in only nine structures.

5. CONCLUDING REMARKS

At this time, it is not possible to draw general conclusions. More information is expected from other design offices. Fruitful data will be obtained at the occurrence of future ground motions. However, it is evident that RC frames with non-ductile detailing and waffle slab structures are the types of vertical system with the largest number of retrofits. Jacketing and RC walls are the most common techniques in CENAPRED sample, along with bracing with prestressing cables.

The wide use of Q=2 for the design of rehabilitation schemes is consistent with the conservative approach followed by most structural engineers. Indeed, after the 1985 earthquakes, it was common that engineers relied on the original structure as capable for carrying vertical loads only, so that the lateral forces induced by the earthquake motions were to be resisted by the rehabilitation scheme added. In some instances, crude assumptions on the contribution of the existing structural system for resisting the lateral loads were made based on a great deal of engineering judgement.

Due to the relative low strength and low stiffness of the soil in the lake bed zone area in Mexico City, medium and high rise buildings required strengthening of the foundation; this was particularly the case when RC walls were added. Frequently, the foundation strengthening amounted for half of the total cost of the rehabilitation (including civil engineering work only), and evidently dictated the feasibility of the project. The existing structure imposed particular challenges for pile driving from the basement, and grade beam jacketing so that understanding the foundation behavior will be of paramount importance.

Although the progress of the project has been slow, results will certainly contribute to improve our knowledge on the behavior of rehabilitation schemes, and will aid in developing more reliable evaluation procedures and technical guidelines for building retrofitting.

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REFERENCES

1. ROSENBLUETH E., and MELI R., The 1985 Earthquake: Causes and Effects in Mexico City. Concrete International, American Concrete Institute, 1986, pp. 23-34.

2. JIRSA J.O., Repair of Damaged Buildings - Mexico City. Proceedings of the Pacific Conference on Earthquake Engineering, New Zealand, Vol. 1, 1987, pp. 25-34.

3. DEPARTAMENTO DEL DISTRITO FEDERAL, Reglamento de Construcciones para el Distrito Federal. Gaceta Oficial del Departamento del D.F., 1987, 100 pp.

4. DEPARTAMENTO DEL DISTRITO FEDERAL, Sismos de 1985 - Control de Edificaciones, México, D.F. 1985-1988. México D.F., 1988, 176 pp.

5. BREÑA S.F., An Overview of Rehabilitation Techniques Used in Reinforced Concrete Buildings in Mexico City. M.Sc. Thesis. The University of Texas at Austin, 1990,180 pp.

6. ALCOCER S.M., R/C Frame Connections Rehabilitated by Jacketing. ASCE Journal of Structural Engineering, Vol. 119, No. 5, 1993, pp. 1413-1431.

7. JIRSA J.O., Repairing and Strengthening of Reinforced Concrete Frame Systems. Proceedings of the Conference on the Repair and Rehabilitation of Infrastructure of the Americas, Mayagüez, Puerto Rico, 1994.

8. RAMIREZ A., Estadísticas de edificios rehabilitados en la ciudad de México después de los sismos de 1985. B.Sc. Thesis. National Autonomous University of Mexico, 1995.

9. AMERICAN CONCRETE INSTITUTE, Building Code Requirements for Reinforced Concrete (ACI 318-89) and Commentary. Detroit MI, 1989, 353 pp.