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Design and behavior of reinforced concrete structure, earthquake engineering, rehabilitation of structures

Luis, I am pleased to have the opportunity to participate in this symposium honoring your achievements. You have devoted your career to improving our understanding of the hazards that we face in seismic zones. I have always appreciated your calm demeanor, infectious smile, and good humor; just as I have the intensity of your desire to make the world a safer place for people who must live with natural disasters.

Your leadership in the earthquake engineering community in Mexico City, in the Americas, and worldwide have brought great distinction to you and your Mexican colleagues and you have been a steady voice during times of stress and distress. I have always been grateful for the assistance you provided following the 1985 earthquake when I and others from the University of Texas came to study the aftermath of that earthquake. For us it was a wonderful learning experience—and probably the closest to Texas that we will ever see. I know it was a time when you were totally occupied with duties related to recovery following the earthquake but you and your colleagues took the time to greet and brief us and to make the visit productive.

Earthquake engineering is a field where there are no boundaries or limits to the exchange of information and knowledge. We learn together or we fail together. You have been a great proponent for the exchange of ideas to reach our goals. You are a role mode *par excellence*, a good friend, and a valued colleague. Congratulations on this occasion and on all that you have achieved.

Jim Jirsa
26 August 2005

CHALLENGES IN SEISMIC REHABILITATION OF STRUCTURES

ABSTRACT

There are few problems in earthquake engineering that are more complex than those associated with understanding the performance of existing buildings and determining how that performance can be improved to mitigate damage and loss of life in future earthquakes. The objective of this presentation is to describe some of the lessons learned from the Mexico City experience, to review some of the research that has been done, and to discuss the challenges that lie ahead.

Introduction

The 1985 Mexico City earthquake provided the impetus for studies of rehabilitation techniques that would reduce the risk posed by existing buildings. The development of design guidelines and updating of such documents is usually accomplished through a combination of laboratory studies and field experience. Furthermore, the issues are not easily studied in parts or in small scale because of the complexity of the interactions between different elements of the existing structure and between the existing structure and new elements added during rehabilitation. The variety of different situations is immense. As a result, one of the best sources of information for understanding the behavior of existing structures before or after rehabilitation is reconnaissance studies after an earthquake occurs. The lessons learned in Mexico City have been repeated in other mega-cities located in regions of high seismicity.

In rehabilitation design, the structural engineer is faced with selecting an option that will correct the deficiencies in the building and satisfy the owner of the structure and the local building officials. In some cases, the existing lateral force-resisting elements may be so difficult and expensive to modify that new alternate lateral load-carrying elements are introduced into the structure. To accomplish the task facing the designer, knowledge of building performance both from field reconnaissance and from laboratory studies is needed. Much can be learned from an understanding of the rehabilitation techniques implemented by others. In this regard, Mexico City after 1985 is a rich source of information.

Overview of Building Damage from 1985 Earthquake

Most of the buildings damaged during the 1985 earthquake were located in the lake bed zone. Another important characteristic was the almost harmonic motion registered in the lake zone and the high energy content at periods greater than one second. The duration of strong motion between about 40 and 70 seconds and the harmonic characteristics of the ground motion created significant ductility demands on buildings and increased both the extent and level of damage (Fundacion ICA, 1988).

Many engineered buildings that were seriously damaged during the 1985 earthquake were medium height, reinforced concrete buildings (6 to 15 floors) that had natural periods close to period of the dominant ground motion. The dynamic response of these moment-resisting frame structures was greatly amplified. Buildings with masonry bearing walls performed quite well during the earthquake. Bearing wall buildings were generally less than 5 stories high and were much stiffer than framed buildings of comparable height.

In Table1, information on 379 buildings that partially or completely collapsed or were severely damaged during the 1985 earthquake is summarized (Iglesias and Aguilar 1988). The buildings are listed according to structural type and number of stories. Concrete buildings represent 86% of the total, 47% were built between 1957 and 1976, and 21% were built after 1976. Damage was concentrated in buildings with 6 to 15 stories and most of these mid-rise buildings were concrete structures.

Table 1 Summary of Damage

TYPE OF STRUCTURE	EXTENT OF DAMAGE	NUMBER OF STORIES				TOTAL
		<5	6-10	11-15	>15	
R/C Frames	Collapse Severe	37 23	47 62	9 14	0 0	93 99
R/C Frames & Shear Walls	Collapse Severe	0 2	1 1	0 2	0 1	1 6
Waffle Slab	Collapse Severe	20 6	31 33	6 19	0 1	57 59
Waffle Slab & Shear Walls	Collapse Severe	0 0	0 2	0 3	0 0	0 5
R/C Frames & Beam-Block Slab	Collapse Severe	3 0	0 1	0 2	0 2	3 5
Steel Frames	Collapse Severe	6 0	1 2	3 1	1 3	10 6
Masonry Bearing Walls	Collapse Severe	8 19	0 1	1 1	0 0	9 21
Masonry B. Walls with R/C Frames in Lower Stories	Collapse Severe	1 3	0 1	0 0	0 0	1 4
TOTAL	Collapse and Severe	128	183	61	7	379

The main modes of failure that were observed in the 1985 earthquake are listed in Table 2. The results were obtained from a survey of 331 buildings in the most affected zone in Mexico City that represented the majority of severely damaged or collapsed buildings (Meli 1987).

Table 2 Type of Damage (Meli, 1987)

MODE OF FAILURE OBSERVED	% OF CASES
Shear in columns	16
Eccentric compression in columns	11
Unidentified type of failure in columns	16
Shear in beams	9
Shear in waffle slab	9
Bending in beams	2
Beam-column joint	8
Shear and bending in shear walls	1.5
Other sources	7
Not possible to identify	25

Structural configuration problems were a major cause of failure. Most configuration problems were associated with the contribution of non-structural elements to the building response. Of the buildings that suffered collapse or severe damage, 42 percent were corner buildings (Rosenblueth and Meli, 1986). Changes in stiffness or mass over the height of the building also were a contributing factor. Changes in stiffness were due to drastic changes in the structural configuration or changes in the size or the longitudinal and transverse reinforcement in columns, or to the location and number of infill walls. Abrupt mass changes resulted from floor dead loadings which were considerably greater than that for which the building had been designed originally. Building pounding was quite common during the 1985 earthquake because of the proximity of adjacent buildings. Much of the column damage can be attributed to pounding especially when the slab levels of two adjacent buildings did not coincide.

It should be noted that these lessons had been learned in previous earthquakes elsewhere in the world and they have been relearned since 1985. Why we continue to see the same problems may be the result of paying insufficient attention to observations from previous earthquakes, political and financial constraints that limit the implementation of new techniques and new codes, or a lack of data on which to base decisions that would lead to a reduction in losses.

Features of Rehabilitation Techniques Used in Mexico City

A report on the rehabilitation work in Mexico City and details of 12 case studies in which different techniques were used was prepared by a team of US and Mexican engineers (Aguilar, et al, 1996; Brena 1990; Iglesias, et al, 1988; Teran, 1988).

Modification of Existing Elements

In Mexico City, concrete jacketing was the most common technique used to increase stiffness and ductility as well as the axial, flexural, and shear strength of existing elements. To develop yield in the longitudinal bars, continuity had to be provided at the ends of the element. For columns this was done by extending bars through the slabs as shown in Figure 1. For beams, the reinforcement was extended through the column core or was bent around the original column. In most cases, the jackets consisted of angles at the corners with straps welded to provide a continuous hoop around the column as shown in the Figure 1.

Figure 1. Examples of column jacketing

In many structures, material was added to increase the size of frame elements that were damaged or that had inadequate strength for design lateral loads. To obtain monolithic behavior, the existing material surface was prepared by roughening the old concrete surface and using epoxy grouted dowels embedded in the concrete interface. Because the lake zone has such difficult soil conditions, many structures were rehabilitated with beam and column jackets to strengthen the existing moment-resisting frame (Figure 2) and avoiding costly modifications to the foundation.

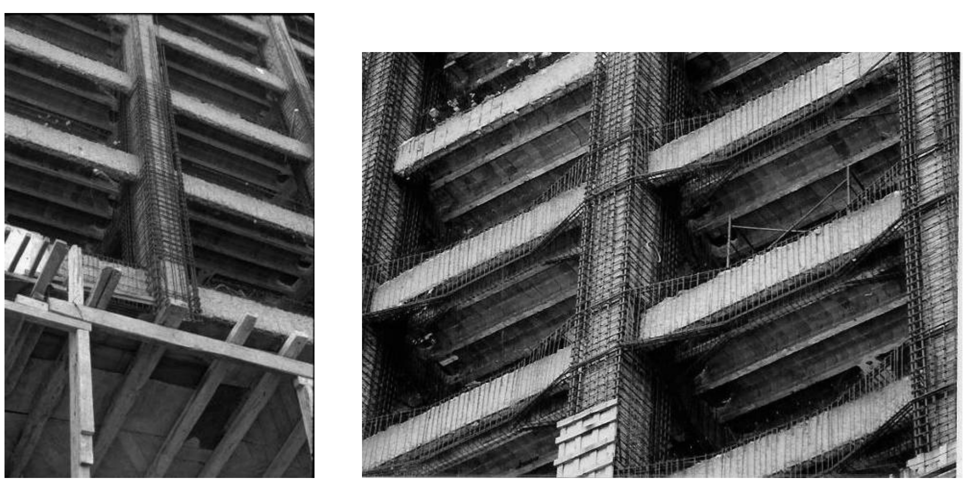


Figure 2. Jacketing of moment-resisting frame.

Addition of new walls

Concrete shear walls were used to eliminate stiffness eccentricities in a building or to increase lateral load carrying capacity. The new walls were located in the perimeter of the structure thereby reducing interior interference. Wall reinforcement was made continuous over the height of the building. Holes were bored into the slab to allow continuity of longitudinal reinforcement, improve the force transfer between the wall and the slab, and allow better concrete compaction near the wall-slab interface. If there were beams in the perimeter frames, the walls had to be offset to pass the longitudinal reinforcement. Structural wall were attached to existing columns whenever possible so that gravity forces would reduce the uplift generated at the ends of the wall due to overturning moments as lateral loads increased. Distributed wall elements provided increased lateral capacity but did not result in large forces applied to the foundation as would the long walls shown in at the left of Figure 3. The addition of new "wing wall" elements to a moment resisting frame can be seen in Figure 4. .

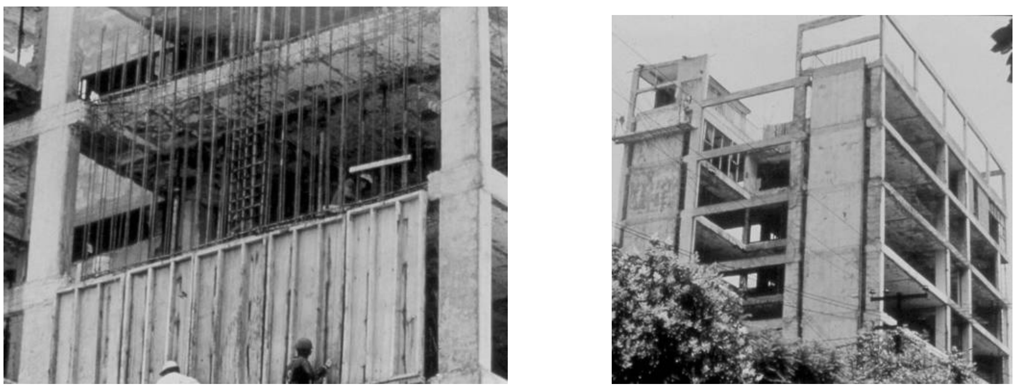


Figure 3. Addition of wall.

Figure 4. Addition of distributed wall elements.

Addition of steel braces

The key feature of this technique was anchorage of steel elements to the existing concrete structure. In some cases, braces were welded to collars or steel jackets that surrounded the columns. Steel column jackets provided also provide additional column capacity to resist the vertical forces generated by the steel braces. In other cases, steel elements located in the perimeter frames were fixed using anchors into the concrete or through bolts clamp the brace against the exterior face of columns floor beams. Infill braces were used when the existing beams and columns had adequate shear capacity to resist the lateral forces induced by the braces. In Figure 5, several steel bracing systems are shown.

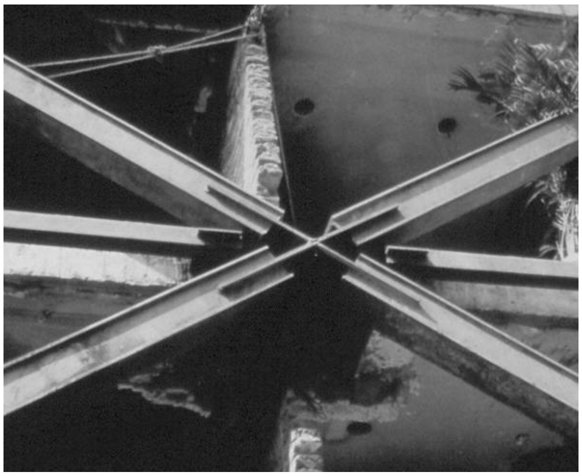


Figure 5. Steel bracing systems

Addition of Cable Bracing

Tension braces or cables were used to eliminate the problems associated with inelastic buckling of bracing systems and to take advantage of the original structure with minimal modifications. In many cases the axial loads generated by the cables required that columns be strengthened by one of the techniques described previously.

Figure 6 Cable bracing systems

Research on Rehabilitation Techniques

The most common deficiencies in existing reinforced concrete structures tend to be related to detailing of transverse reinforcement, continuity of primary reinforcement, and cross-sectional area of lateral force-compression resisting elements. In some cases, the deficiency is the result of changes in design codes that require larger lateral force resistance and more ductility at critical locations where hinges are expected to form, and in other cases the deficiency may be due to errors in construction, changes made by owners or tenants that have reduced the lateral capacity or ductility of the structure, or by changes in the occupancy of the structure that result in higher loads on the system. To provide data for use in developing design guidelines for rehabilitation, an extensive research effort was carried out in the US. Although, work was underway prior to the 1985 earthquake, the Mexico City experience resulted in an acceleration of the research activity. A brief outline of that research follows.

Column Jacketing for Weak Column-Strong Beam Frames

Wing walls

One of the most common types of existing systems in the US are those that have weak column-strong beam frames. The columns have inadequate shear capacity to develop column hinges and brittle shear failures occur. The weak column system has been a key feature in much of the research conducted in the past 25 years at the University of Texas in collaboration with Degenkolb Engineers in San Francisco. A 3 story-2 bay frame was strengthened using "wing walls" as shown in Fig. 7 (Bush, *et al.*1990).

Figure 7. Test frame with strong beams and weak columns and strengthening with wing walls

Jacketing of Damaged Column

In Figure 8, the cross section of a severely damaged column in the frame structure is shown. The damaged columns were jacketed and the frame was retested. The damaged concrete in the existing column had little effect on the calculated strength of the column assuming that the section was monolithic (Stoppenhagen, et al, 1995).

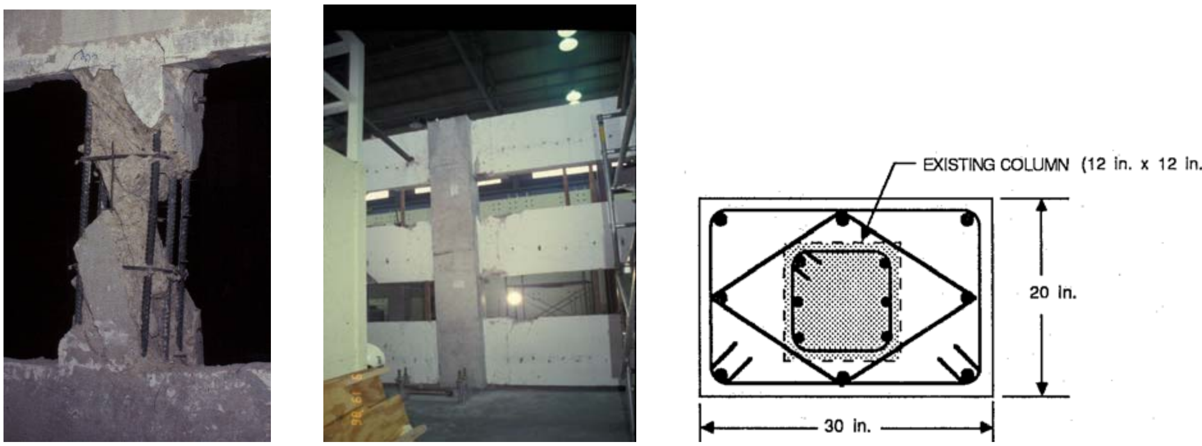


Figure 8. Damaged existing column encased in new section

Shotcrete or Cast-in-Place Jackets to Improve Shear of Ductility

Another technique that was studied was retrofitting weak columns with concrete jackets. Figure 8 shows a column jacketed with shotcrete over a new cage of reinforcement to provide added confinement and shear capacity (Bett, *et al.* 1988). A series of beam-column joints (shown on the right in Figure 8) was tested at the University of Texas as part of a joint CONACYT/NSF research effort (Alcocer and Jirsa, 1993).

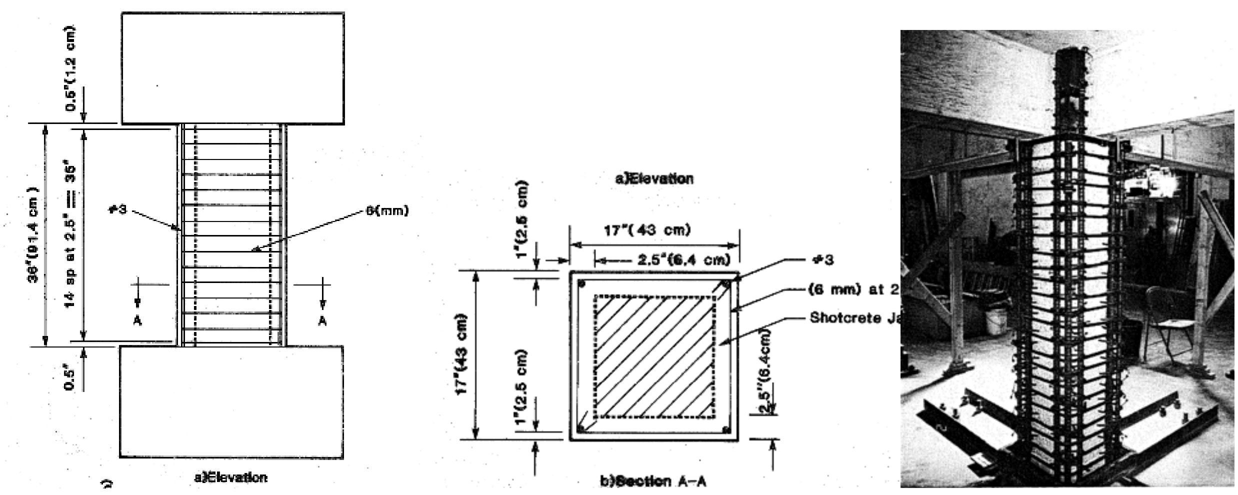


Figure 8. Column jackets

Steel Jackets for Improving Splice or Anchorage Capacities

In some existing structures, a major deficiency is the lack of sufficient anchorage or splice length at critical locations, such as the bottom of a column where a splice is located for facilitating construction. In many older structures, the splice was designed for compression only. However, when the structure is subjected to ground motions, the splices may be at a location where flexural hinging develops. The compression splice can not develop tension and a premature failure occurs at that location. Such details are not easily corrected using concrete jackets. A series of tests was conducted using steel jackets to improve the confinement in the hinging region and the splice strength (Aboutaha, *et al.* 1996, 1999-1). These splices also become critical if the column in which they are located is part of the boundary element for new infill or structural walls. Confinement is excellent near the corners where the steel plates are connected but the efficiency of the steel plates reduces as the distance from the corner increases. To improve the confinement away from the corners, some plates were anchored as shown in Figure 9.

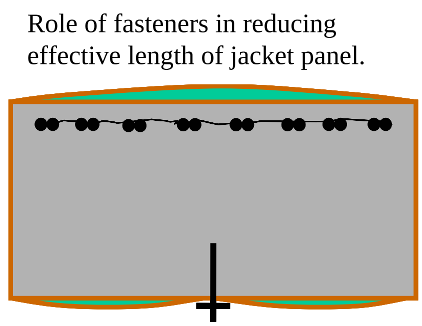
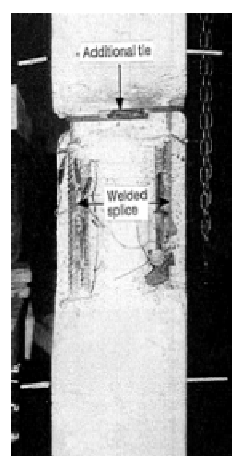
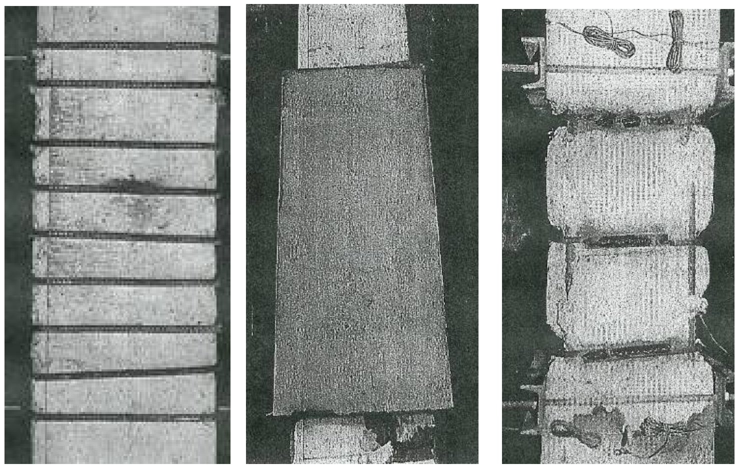


Figure 9. Steel jacket to improve splice capacity

Confinement of Splices Using Plates or Reinforcing Bars

Another series of specimens with inadequate splice lengths was tested to determine the effectiveness of several other details shown in Figure 10 for providing confinement (Valluvan, *et al.* 1993). The section contained four longitudinal bars, one in each corner.





a) Welded straps and angles b) External ties c) Grouted external ties d) Cover removed for new ties e) Welded splices

Figure 10. Confinement added along splice length

Steel jackets for improving shear capacity of columns

A series of tests was conducted to study the effectiveness of steel jackets for strengthening shear deficient columns (Aboutaha *et al.* 1999-2).

Addition Of Structural Walls

Shotcrete or cast-in-place infill walls

One of the simplest schemes for strengthening a structure is to remove existing non-structural infill walls and replace them with reinforced concrete walls that are well connected to the existing frame. The use of shotcrete provides a way of placing the material without the need for concrete formwork and also eliminates the problem with consolidating concrete against the bottom of the beams or floor (Jirsa 1996). Three shotcrete infill walls were tested—one solid wall, one with a window, and one with a door opening (left side in Figure 11). In addition two cast in place walls were tested—one with a door and one with a new wall cast against the existing frame rather than as an infill (right side of Figure 11). By facing the wall on the columns the wall bypasses the frame and makes the process somewhat easier to realize in field applications.

Figure 11. Frames prior to application of shotcrete or cast-in-place infill wall

Studies were carried out to determine the factors that influence shear transfer between new concrete cast against an existing concrete surface. The variables at the interface included the number and spacing of bars crossing the interface, the roughness of the interface, interface material (fresh concrete cast against existing concrete, gap filled with dry pack material, epoxy), and position of casting (horizontal, vertical, or overhead). The results of these tests are reported in Bass *et al.* 1989.

Precast Panel Infill Walls

In order to minimize the amount of concrete that must be cast-in-place when new walls or infills are added to an existing structure, a scheme using precast panels was designed and tested (Frosch *et al.* 1996). The concept was investigated with a two-story test specimen shown in Fig. 12. The arrangement of the precast panels is shown. The panels had keyed edges to improve shear transfer and the grouted joints between panels contained continuous vertical and horizontal wall reinforcement. Vertical post-tensioning tendons were installed at the ends of the walls near the columns to provide tensile capacity for the columns that had inadequate splice lengths.

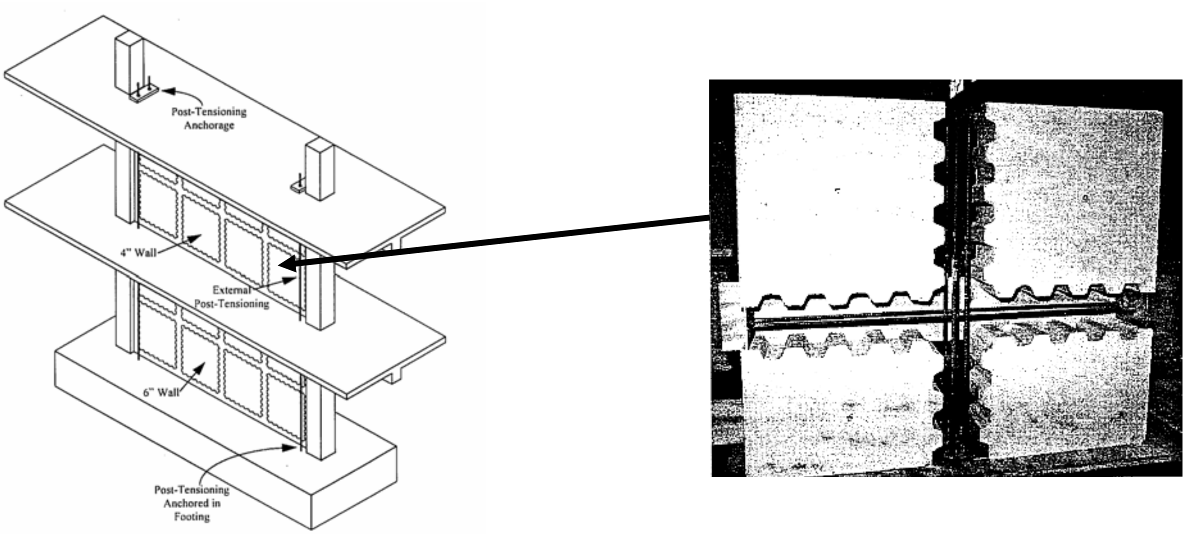


Figure 12. Precast,post-tensioned infill wall system

Observations

The purpose of the tests discussed above was to provide details that would allow desirable mechanisms of failure to develop in existing buildings—flexural hinging if possible. In order to accomplish this objective, the tests indicated that it is essential to provide the following conditions:

- Members must be adequately confined to prevent concrete crushing failures at regions of high moment or compression.
- Primary flexural reinforcement must be continuous or spliced adequately to allow the reinforcement to yield.
- Transverse reinforcement or external jackets must be provided to prevent shear failure before flexural hinging develops.
- The transfer of forces between new and existing concrete surfaces must be sufficient to prevent excessive slip from developing along the interface and to permit the elements that are made up of both new and old concrete to be designed as monolithic sections.

Future Challenges

For a twenty-year period, a great deal of experimental research was conducted that led to the development of guidelines that are now used for the evaluation of existing buildings. However, the limitations of that research are apparent as designers attempt to implement those guidelines. More research is needed and the cost of that research will be much higher than before because large-scale test assemblies or portions of structures will need to be tested. There is a need for tests of structures in-situ because we need to understand better structure-foundation-soil interactions and using existing materials. As a profession we must define research programs that will capture the imagination of political leaders in an era of major research expenditures for biomedical studies, nanotechnology, space exploration, and environmental concerns. Unlike many fields, the civil engineering and infrastructure field has no dominant industries. It is a very diverse industry with many competing elements and no strategic plan.

One of the problems we face is that overall spending for research in the US is not increasing in real dollars. Research budgets have stagnated in the face of increasing needs and higher costs. The problem is illustrated in Figure 13. In view of the trends shown, it will be necessary for our profession to articulate a vision of the future as influenced by civil engineers that is so compelling that the public will call on our leaders in government and industry to do something. In fact, this is what happens after major disasters or crises when funding flows to address problems whose solution is seen as essential to society. The increase in earthquake engineering research following major events (generally defined by the number of lives lost) is an example of such a reaction. If we want to compete with our colleagues in the sciences and medicine for the shrinking funding pool, we must become as proactive and creative as they have been.

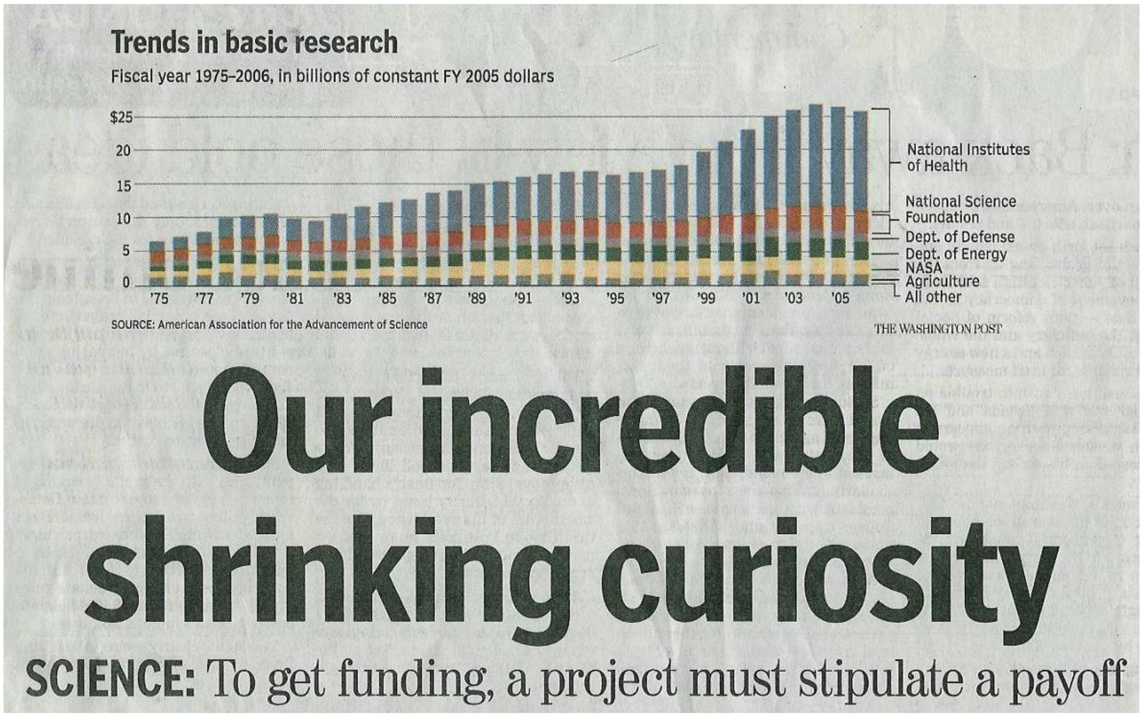


Figure 13. Research Expenditures in the US from 1975 to 2006*

However, in many of our universities and engineering programs, declining civil engineering

* From an article in the Austin American Statesman, May 1, 2005 written by Rick Weiss of the Washington Post

Enrollments are an indication that civil engineering is a mature field and that little new is happening. As a result, funding is diverted from civil engineering to rapidly growing fields such as communication or information technology and biomedical engineering. But as the world's population expands, the demand for more extensive and complex civil infrastructure, clean environment, and mitigation of the effects of natural hazards in the world's mega-cities will not diminish and civil engineering must play an essential role in addressing those issues.

Concluding Remarks

I hope that our celebration of the accomplishments of Prof. Luis Esteva will stimulate us to get involved to determine our future rather than to sit by and let others determine it. I believe that society values our contributions and holds civil engineers in fairly high esteem. As earthquake specialists, we have an opportunity to build on the exchanges of knowledge that are routine in our field and make the world more livable and safer.

Acknolwedgements

Without the help and friendship of many colleagues from Mexico, it would not have been possible to compile information on buildings that were damaged and/or rehabilitated in Mexico City. Special thanks to Jesus Iglesias, Roberto Meli, and Enrique del Valle for their assistance in the research that followed the 1985 earthquake. Finally, I would like to express my appreciation to the many graduate students whose efforts made the research described in the paper a reality.

References

Aboutaha, R., Engelhardt, M.D., Jirsa, J.O., and Kreger, M.E. (1996). Seismic Retrofit of R/C Columns Using Steel Jackets, *ACI* SP-160, Seismic Rehabilitation of Concrete Structures, pp. 59-72.

Aboutaha, R.S., Engelhardt, M.D., Jirsa, J.O., and Kreger, M.E (1999-1). Rehabilitation of Shear Critical Concrete Columns by Use of Rectangular Steel Jackets, *ACI Structural Journal* 96 (1), American Concrete, pp. 68-78.

Aboutaha, R.S., Engelhardt, M.D., Jirsa, J.O., and Kreger, M.E. (1999-2). Rehabilitation of Shear Critical Concrete Columns by Use of Rectangular Steel Jackets, *ACI Structural Journal* 96 (1), pp. 68-78.

Aguilar, J., Brena, S. F., del Valle, E., Iglesias, J., Picado, M., Jara, M., Jirsa, J. O., (1996). Rehabilitation of existing reinforced concrete buildings in Mexico City: Case studies, PMFSEL Report 96-3, University of Texas at Austin.

Alcocer, S.M., and Jirsa, J.O. (1993). Strength of Reinforced Concrete Frame Connections Rehabilitated by Jacketing, *ACI Structural Journal* 90 (3).

Bass, R.A., Carrasquillo, R.L., and Jirsa, J.O. (1989). Shear Transfer Across Concrete Interfaces, *ACI Structures Journal* 86 (4), pp. 383-393.

Bett, B.J., Klingner, R.E., and Jirsa, J.O. (1988). Lateral Load Response of Strengthened and Repaired RC Columns, *ACI Structural Journal* 85 (5), pp. 499-508.

Breña, S. F. (1990), An overview of rehabilitation techniques used in reinforced concrete buildings in Mexico City, Thesis, Master of Science in Engineering, The University of Texas at Austin, December.

Bush, T., Talton, C. Roach, and Jirsa, J.O. (1990). Behavior of a Structure Strengthened Using Reinforced Concrete Piers, *ACI Structural Journal* 87 (5), pp. 557-563.

Frosch, R.J., Li, W., Jirsa, J.O., and Kreger, M.E. (1996). Retrofit of Non-Ductile Moment-Resisting Frames Using Precast Infill Wall Panels, *Earthquake Spectra* 12 (4).

Fundacion ICA, A.C., (1988). Experiencias derivadas de los sismos de septiembre de 1985, Limusa, Mexico, D.F.

Iglesias, J. and Aguilar, J., (1988). Identificación de daños ocasionados por los sismos de 1985, 1979 y 1957 en la Zona Metropolitana, Estudios de Sismicidad en el Valle de Mexico, *3a Parte, Capitulo III, Anexos I and II, Departamento del Distrito Federal and Centro de las Naciones Unidas para los Asentamientos Humanos* (HABITAT), Mexico, D.F.

Iglesias, J., Robles, F., De La Cera, J. and Gonzalez, O., (1988). Reparación de estructuras de concreto y mamposteria, Universidad Autónoma Metropolitana, Mexico, D.F.

Jirsa, J.O. (1992). Response of Frame-Infill Wall Structures, Transactions of Workshop on Non-Linear Seismic Analysis of Reinforced Concrete Buildings, Bled Slovenia, July.

Meli, R., (1987). Evaluation of performance of concrete buildings damaged by the September 19, 1985 Mexico Earthquake; *The Mexico Earthquakes-1985: Factors Involved and Lessons Learned*, ASCE, pp. 308-327.

Rosenblueth, E. and Meli, R., (1986). The 1985 Earthquake: Causes and effects in Mexico City, *Concrete International*, May, pp. 23-34.

Rosenblueth, E., Emergency regulations and the new building code, *The Mexico Earthquakes-1985: Factors Involved and Lessons Learned*, *ASCE Special Publication*.

Stoppenhagen, D. R., Jirsa, J. O., and Wyllie, Jr., L. A. (1995). Seismic Repair and Strengthening of a Severely Damaged Concrete Frame," *ACI Structural Journal* 92 (3), pp 177-197.

Teran, A., (1988), Review of repair techniques for earthquake damaged reinforced concrete buildings, Thesis, Master of Science in Engineering, The University of Texas at Austin, December.

Valluvan, R., Kreger, M.E., Jirsa, J.O. (1993), "Strengthening of Column Splices for Seismic Retrofit of Non-ductile RC Frames," *ACI Structural Journal* 90 (4), American Concrete Institute.