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DESIGN PHILOSOPHY FOR SEISMIC UPGRADING OF BUILDINGS: A LATIN AMERICAN PERSPECTIVE

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ABSTRACT

The process of seismic rehabilitation of damaged buildings and upgrading of existing ones, should be based on a sound and consistent design philosophy. Meeting the requirements of seismic codes, whose prime objective is to avoid collapse and protect human life, is not enough. Seismic codes allow inelastic behavior of the structural systems resulting, during high intensity earthquakes, in the formation of plastic hinges and a certain degree of structural failure, usually accompanied by severe nonstructural damage and high economic losses.

As shown during recent destructive seismic events, buildings which showed an adequate structural behavior, with little or no failure of the lateral load resistant system, were declared inhabitable due to severe secondary damage to architectural components and electrical and mechanical facilities, resulting in high economic losses and in a complete failure to the owner.

In the structural strengthening and seismic rehabilitation of buildings, it is not enough to add capacity to the lateral load resistant system. Nonstructural damage is proportional to drift or relative lateral interstory displacements. Therefore, the flexibility of the structure must also be controlled. Modifying the structural system by adding elements that provide adequate stiffness to reduce lateral displacements is part of the design philosophy adopted by the author. These considerations are fundamental for essential facilities, which must continue in service after a destructive event, but are also valid for normal occupancy buildings as a mean of reducing non-structural damage and economic losses.

The author presents the concept of seismic upgrading of buildings, from the perspective of a small developing country: Costa Rica. The adopted solutions, complying with the aforementioned criteria, correspond to the common construction practice in the country, but the expressed philosophy and criteria can be applied to other regions in the world. The use of structural walls and bracing systems are shown to be an efficient way to add strength and to control flexibility in order to reduce lateral displacements, damage and economic losses. Costa Rica's long tradition in the structural strengthening and upgrading of public and private buildings shows the effectiveness of these measures. They resulted, in general, in a good behavior of buildings and essential facilities during an intense seismic activity that affected the country between 1990 and 1991.

KEYWORDS

Buildings; upgrading of buildings; seismic upgrading; retrofit; structural strengthening; seismic performance

INTRODUCTION

In this paper, the term *"retrofit"* has been deliberately substituted by the terms "*structural strengthening*" and "*seismic upgrading*". The term *retrofit* is not registered in most of the English dictionaries and encyclopedias. The Latin prefix "*retro*" denotes *regression, to go backward* and in loan words such as *retrogress* means *going backward from a better to a worse state - to decline to a worse condition*. As such, *retrofit* has a connotation of going backward from a superior condition of a building to a lower one and implies the contrary of implementation or improvement. *Retrofit* seems to be an incorrect term to denote measures of strengthening the lateral load resistant system and improving the seismic performance of buildings. The author considers that the aforementioned term should be substituted by *seismic upgrading* (Sauter, 1996).

ADOPTION OF STRENGTHENING AND UPGRADING MEASURES

Measures for structural strengthnening and for improving the seismic behavior of buildings are adopted when a.) the building has suffered damage as a consequence of a seismic event, and b) a study determines that an existing building does not meet seismic code requirements, nor advanced criteria of structural configuration and of earthquake-resistant design, resulting in a building vulnerable to suffer damage and even collapse.

When a structure's resistant elements have suffered damage, it is obvious that the building must be repaired and strengthened (Degenkolb, 1983; Bertero *et al.*, 1989; Sauter, 1992). However, numerous buildings that have suffered moderate secondary damage and no apparent structural failure, have been strengthened and seismically upgraded in order to improve its performance and reduce economic losses caused by future earthquakes (Sauter, 1993 and 1995). The economic loss related to cracking of walls, breaking of windows and falling of suspended ceilings (Fig.1), as well as damage to electrical and mechanical facilities, may decide the owner to strengthen the building, despite the absence of failure in structural elements.

The results of a seismic vulnerability study can also decide the adoption of strengthening and upgrading measures, even in existing buildings that have not suffered any damage during previous earthquakes (Wyllie, 1981; Sharpe, 1986, Perbyx *et al.*, 1989; Sauter 1995). A vulnerability study is necessary for essential facilities and buildings with high occupancy. But it is also necessary when the reduction of economic losses is a desirable objective.

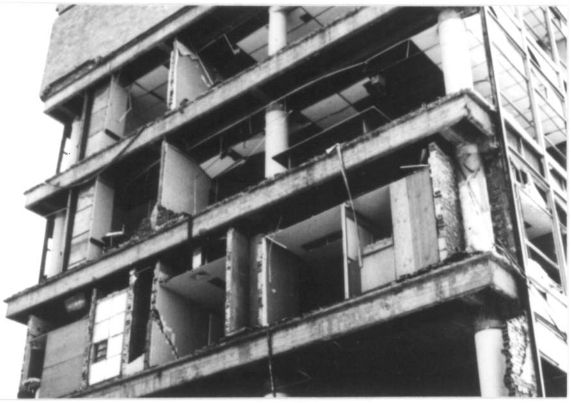


Fig.1 Damage to architectural components and electromechanical systems in a hospital in Mexico City after the 1985 earthquake.

Fig.2 Hospital evacuated due to severe secondary damage after the Limon, Costa Rica, 1991 earthquake.

It should be noted that the structural strengthening practice in Costa Rica has not only been a consequence of a governmental decree. In fact, in the majority of cases, it has been a voluntary and wise decision of the owners, aware of the seismic hazard, that have opted to invest in improving the seismic performance of their buildings. Surprisingly, in Costa Rica the control of nonstructural damage and the reduction of economic losses have been the main incentive that led to the adoption of preventive seismic upgrading measures (Sauter, 1992 and 1995). It seems that owners feel that avoiding collapse and protecting human life, as expressed in seismic code philosophy, is an incomplete objective (Sauter, 1989 and 1991).

SEISMIC CODE PHILOSOPHY

These considerations make us analyze the philosophy of the majority of the current seismic codes, which is summarized as follows:

* Resist low intensity and frequent earthquakes without damage,
* Resist moderate earthquakes without structural failure, and with moderate nonstructural damage,
* Resist high intensity earthquakes without suffering collapse, allowing inelastic behavior and severe secondary damage.

The prime objective is to avoid collapse and protect human life. Even when codes implicitly have rules to limit to lateral displacements and to control damage, they do not express clearly that reducing economic losses should also be a fundamental objective of seismic resistant design (Bertero, 1989; Sauter, 1991 and 1992). It is allowed that, during high intensity earthquakes, the structures may have inelastic behavior, which results in a certain degree of structural failure, and major damage to walls and architectural components.

This philosophy is obviously inadequate for essential facilities, such as hospitals and communication centers, that must continue in service after a seismic catastrophe (Wyllie, 1981; Sharpe, 1986, Sauter, 1991). The Mexico 1985 earthquake was clear to this respect: it showed that avoiding collapse is not enough, since numerous hospital buildings had to be evacuated and were out of service due to severe damage to architectural components and electromechanical systems (Fig. 1). The same happened after the San Salvador 1986 earthquake; three hospitals were rendered out of service due to severe nonstructural damage (Sauter, 1987). The Limon, Costa Rica 1991 earthquake caused significant damage to architectural components in a hospital building as shown in Fig.2, resulting in the evacuation of the building even when it did not suffer structural failure (Sauter, 1993).

The collapse of telecommunication centers and loss of equipment and telephone lines after the Mexico 1985 and San Salvador 1986 earthquakes have been extensively studied and evaluated in relation to the effects of seismic events in essential facilities.

Current seismic codes recognize that essential facilities must be designed for a higher seismic demand and must have a larger capacity to resist seismic forces than a building of normal occupancy. In general, they require an increment in the seismic coefficient through the importance factor S, whose value ranges between 1,2 and 1,5. The Costa Rica Seismic Code (CFIA, 1986) adopts a different approach in its latest edition, assigning to essential facilities a longer lifetime (100 years) and a lower probability of exceedency (0.20) than those assigned to normal occupancy buildings (50 years and a 0.40 probability), resulting in return periods of 500 and 100 years respectively. These criteria result, as shown in Fig.3 in higher spectrum values, compared to other norms such as SEAOC, California (Sauter, 1991 and 1995).

However, it must be understood that increasing the seismic coefficient and the design lateral forces, does not necessarily result in a better seismic performance of essential facilities. In these cases, it is not enough to increase strength. It is necessary to control the flexibility of the building by modifying the structural system and by including resistant elements that provide stiffness in order to limit lateral displacements and consequently to reduce nonstructural damage (Sauter, 1992 and 1995).

The philosophy of current codes mentioned before, to avoid collapse and protect human life, is not satisfactory for normal occupancy buildings either. During recent destructive events, buildings designed according to the current seismic code requirements, showed a good structural behavior with small or no damage to the lateral load resistant system, being a success from the point of view of the designer. However, they were a failure from the point of view of the owner since his building was rendered out of service and declared inhabitable due to severe nonstructural damage as shown in Fig.4 (Sharpe, 1986; Bertero *et al.*, 1989, Sauter, 1995). The responsible engineer can hardly justify to his client this failure claiming that he followed the philosophy of the code; the owner will rightfully qualify this philosophy as being wrong. Damage to architectural components and

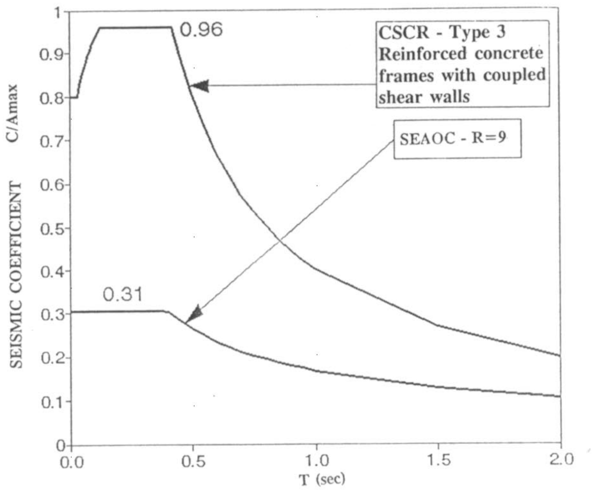


Fig.3 Comparison of design spectra: Costa Rica seismic code and SEAOC, California.

Fig.4 Buildings with flexible frame structure are vulnerable to severe damage. Example of cracked and fallen masonry walls.

electromechanical facilities result in high economic losses that approach the recovery value, and as such may be equivalent to a total loss. From the previous considerations, we conclude that the seismic code philosophy should be reviewed (Sauter, 1991).

FUNDAMENTAL OBJECTIVE: REDUCTION OF ECONOMIC LOSSES

In the process of structural strengthening and seismic upgrading of existing buildings, it is necessary to consider that it is not enough to meet the philosophy of seismic codes, whose prime objective is to avoid collapse and protect human life (Sauter, 1991 and 1992). Seismic code requirements allow inelastic behavior of the resisting structural system during high intensity earthquakes, resulting in formation of plastic hinges and in a certain degree of structural failure, usually accompanied by severe secondary damage and high economic losses.

Since nonstructural damage depends on drift or relative lateral displacements between floors, the designer must pay special attention to controlling such displacements. In the process of improving the seismic performance of buildings, it is not enough to just add strength to the lateral load resistant system. The flexibility of the structure must also be controlled by adding elements that provide adequate stiffness to reduce lateral displacements, and consequently, nonstructural damage (Sauter, 1989, 1991, 1992 and 1995) . This aspect must be considered part of the earthquake-resistant design philosophy, and of the strengthening and upgrading process of existing buildings. These considerations are valid for essential facilities, which must continue in service after a destructive event, and must, therefore, withstand high intensity earthquakes without suffering significant secondary damage. But these criteria also apply to normal occupancy buildings. As it has been shown during recent earthquakes, damage to architectural components and to electrical and mechanical facilities may render a building out of service. The experience shows that buildings that did not suffer structural damage were declared inhabitable due to severe nonstructural damage, and were a complete failure to their owners.

THE CASE OF COSTA RICA

Despite a reduced population of less than 3 million inhabitants, Costa Rica has always been characterized by objectively focusing the seismic hazard to which it is exposed, and it has a long tradition of structural strengthening and seismic upgrading of buildings.

The first effective measure in seismic disaster mitigation in Costa Rica was decided in 1910. Through a governmental decree, the *adobe* or mud brick construction was prohibited 85 years ago and Costa Rica stands now as the only country in Latin America in which *adobe* construction is not used at all (Sauter, 1995). This decision has prevented high death tolls and huge economic losses due to the poor seismic behavior of *adobe* during destructive earthquakes, as experienced in Peru 1970, Guatemala 1976 and Iran 1990.

The tragic experience of death and destruction in neighboring countries, the earthquakes of San Salvador 1965 and 1986, Managua 1968 and 1972, Guatemala 1976 and Mexico 1985, made Costa Rica face the seismic hazard and adopt preventive measures tending to mitigate the impact of future destructive events.

The most successful measure of seismic mitigation adopted in Costa Rica has been the structural strengthening and seismic upgrading of existing buildings. Strengthening of structures began early in 1968, when the first building was strengthened. The building was upgraded not because it suffered any damage, but because of good professional criteria of the architect in charge of remodeling the building. Following his recommendation, the author proceeded to make a study of seismic vulnerability, resulting in the owners decision of strengthening the structure (Sauter, 1992 and 1995).

The practice of seismic upgrading gained strength after the destructive Managua 1972 and Guatemala 1976 earthquakes, which produced a great psychologic impact in the public, and became even stronger after two earthquakes hit Costa Rica in 1983. In 1987 the Government published a decree, making all government entities perform studies of seismic vulnerability of public buildings and essential facilities, encouraging them to adopt seismic mitigation measures and to strengthen vulnerable structures. This gave increased impulse to the seismic upgrading process in Costa Rica.

Numerous essential facilities were seismically rehabilitated. The Costa Rican Institute of Social Security and the Costa Rican Institute of Electricity were pioneers in the field, strengthening many essential facilities. The National Children's Hospital was the first hospital complex that, not suffering any damage as a consequence of previous earthquakes, was strengthened as a preventive measure, as recommended by the author's office. Four main hospitals followed (Sauter, 1993), as well as six three telecommunication centers. In one of them, the upgrading work had been finished just three months before the earthquake of December 1990 hit the city of Alajuela. Not a single telephone line was lost as a consequence of this event, thus confirming the strengthening of buildings as an efficient method to mitigate the effects of destructive seismic events (Degenkolb, 1983; Bertero, 1989; Sauter, 1992 and 1995).

It is interesting to know what has been done in Costa Rica in this field: a total of 140 public buildings, approximately 170 private buildings and more than 20 churches and historic monuments, with a construction area that surpasses 1,5 million square meters, have been subjected to different methods of structural strengthening and seismic upgrading. An astounding number for a small developing country with only 3 million inhabitants.

LATERAL LOAD RESISTING SYSTEMS

In selecting the lateral load resisting system, two different design tendencies have taken form: flexible systems using ductile frames vs. rigid systems using structural walls (Wyllie, 1981; Endo, 1984; Higashi *et al.*, 1984; Bertero et al., 1989; Sauter, 1989, 1991 and 1995). There is an intermediate point of view that considers the use of a composite systems of modified flexibility.

Based on his experience studying the behavior of different structural systems during recent destructive events (Sauter, 1987 and 1993), the author shares his preference for structural systems with controlled flexibility consisting of ductile moment resistant space frames with coupled structural or shear walls. Modifying the structural system including shear walls or braced elements is part of the process of stregthnening and upgrading of buildings.

Systems based solely on ductile space frames, even when the seismic demand is less due to their inelastic response, undergo larger lateral displacements due to their flexibility and the P- delta effect becomes significant. Being the secondary damage proportional to the relative lateral displacements or drift, these systems suffer more nonstructural damage and, consequently, are subject to higher economic losses (Fig. 1, 2 and 4). Flexible systems are also vulnerable to collapse. Structural systems based on shear walls are, on the other hand, stiffer and suffer smaller lateral displacements, and consequently less nonstructural damage. In general, they also show a better seismic behavior (Sauter, 1987 and 1992; Bertero *et al.*, 1989).

Structural walls as part of the lateral load resisting system have proven to be an adequate solution, as shown by the behavior of the Benjamin Bloom Children's Hospital in San Salvador (Sauter, 1987). As shown in Fig.5, two three floor reinforced concrete frame sections collapsed. The 11 story high building that included shear walls did not collapse, even when the walls were not designed according to advanced earthquake resistant criteria. The building suffered only minor structural damage, and was later repaired, strengthened and rehabilitated.

Fig.5 Benjamin Bloom Hospital, San Salvador. Collapse of two three-floor frame structures, while the eleven-floor tower that included structural walls remains standing.

Fig.6 Seismic strengthening by jacketing structural elements. Milling building in Costa Rica.

A conclusion that can be drawn from the evaluation of building performance during earthquakes, generalizing in a very broad sense, is that not all framed structures collapse, but all collapses occur in space framed buildings.

STRUCTURAL STRENGTHENING PROCEDURES

In the process of seismic upgrading of existing buildings, the structural system to be chosen and the strengthening elements to be used depend on the desired degree of protection.

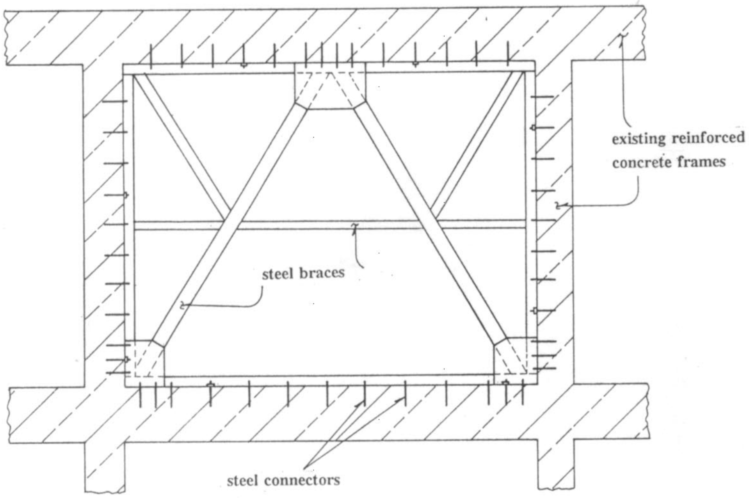
For the strengthening of reinforced concrete structures there are different solutions:

- Jacketing of structural elements: increasing cross sections and steel reinforcement to increase their capacity (Kuroiwa *et al.*, 1980; Degenkolb, 1983; Endo, 1984; Higashi *et al.*, 1984; Sauter, 1995)
- Use of steel bracing elements (Jones, 1985; Badoux *et al.*, 1990; Sauter 1992)
- Inclusion of coupled structural walls to frame systems (Higashi, 1980; Wyllie, 1981; Roach, 1986; Sauter, 1991 and 1995).
- Construction of an exterior system along the perimeter of the building,
- Composite system that combines various of the aforementioned methods.

In Costa Rica all the previous solutions have been used (Sauter, 1989, 1992 and 1995). The first solution, even when it increases the capacity of the system and lightly increases its stiffness, is not very efficient to control the flexibility and does not modify significantly the behavior of framed structures. These structures will continue to be vulnerable to large lateral displacements and to suffer significant nonstructural damage. In the milling tower shown in Fig.6, an eight floor building damaged during the December 1990 earthquake, the stregthening was done by jacketing the columns and facade girders. Nevertheless, these strengthening was completed by adding structural walls in other axes of the structure.

On the other hand, in steel braced systems of strengthened buildings, the elements are subjected to compressive axial forces and are vulnerable to suffer buckling. The transmision of the forces in the bracing system to the existing structural frame system depends on the connections, that should be preferably made using bolts along steel collectors as shown in Fig.7.

Nevertheless, the most common method of seismic strengthening used in Costa Rica are reinforced concrete structural shear walls as shown in Fig.8.



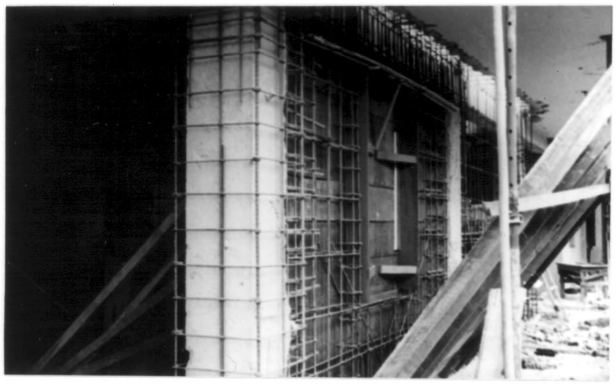


Fig.7 Vertical steel bracing system for a telecommunication center, Alajuela, Costa Rica.

Fig.8 Construction of structural walls coupled to a frame system to limit lateral displacements and reduce nonstructural damage

It is the author's opinion that adding structural walls, even when it imposes some architectural restrictions, in the majority of the cases is a much simpler procedure of modifying and strengthening the structural system, and presents less construction problems. Walls modify a framed structure making it a stiffer resisting system, subject to smaller lateral displacements, resulting therefore in less nonstructural damage and lower economic losses. The walls are, as a consequence, a more efficient structural system with better seismic performance. Comparative cost studies have been conducted in the author's office for different strengthening solutions. The structural wall solution has proven to be the most economical one. Construction firms in Costa Rica, which have acquired experience in the seismic strengthening of buildings, also prefer the structural wall solution for economic and constructive reasons.

CONCLUSIONS

The author's design criteria in seismic upgrading of buildings has been presented as well as the techniques used in Costa Rica for the structural strengthening of reinforced concrete buildings. The fact that structural strengthening of buildings has been a tradition and is widely generalized in Costa Rica is emphasized. Costa Rica is way ahead of the objectives of the International Decade for Natural Disaster Reduction (IDNDR) prematurely adopting preventive measures to mitigate the social and economic impact of destructive seismic events.

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