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EXPERIENCES IN MEXICO. REINFORCING AND BRACING BUILDINGS AFTER THE 1985 EARTHQUAKE. A DESIGNERS POINT OF VIEW

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ABSTRACT

Rehabilitation of buildings damaged by the 1985 earthquake became common practice in structural design, because in many cases functional, economical and safety advantages could be obtained, even though the requirements imposed by the new standards proposed in the Regulations had to be met. These requirements were radically modified after the destructive events of 1985.

The use of steel shapes allowed economical advantages, lower loads and safety, but mainly, construction simplicity and feasibility. This was achieve because it was possible to prefabricate a large part of the reinforcement structure to place it later in the damaged building. These buildings could not be evacuated easily, as for example in some hospitals, schools and telephone exchanges.

The task was sub divided in the following steps:
1) Study and identification of the problem.
2) Analysis and Design in compliance with the Standards
3) Provide an adequate behavior for both structures
4) Careful study of the connections making them simple and optimum.
5) Synthesize construction problems, mainly in occupied buildings.
6) Gather the necessary information to know more about the possible future behavior of rehabilitated buildings.
7) Conclusions

KEYWORDS

Retrofitting; damaged; steel shapes; bracing; simplicity; prefabricate; connections; simplification; construction problems; future behavior.

STUDY AND IDENTIFICATION OF THE PROBLEM

The most important item that engineers face in their professional practice is the decision-making process about the reinforcement, stiffening and foundation aspects of the damaged structure as well as in the case of buildings, which, without having damages, have to meet new regulation requirements.

Reinforce?, Brace?, Underpinning?, How?, With concrete elements?, With steel shapes?, With prestressed cables?, In which position must they be placed?, In which places they will not affect the functionality and the architecture of the building?, Which regulation parameters must be used?, How should they be connected to the existing structure?, Is the proposed solution feasible?, Is its cost reasonable and can the owners pay for it?, Will the new structure behave adequately under new and larger seismic forces?, All of these and many other questions are harassing us and are an faced by structural engineers who work in professional practice of project and design of urban buildings or industrial facilities. This is precisely the kind of problem that they have to face, study and identify accurately.

There are many researchers and engineers who have contributed solutions, some of them brilliant, witty others, mostly of little interest and many of them difficult to build, expensive most of them; but the truly relevant aspect is the fact that structural engineer has to look at what tends to or gets close to the optimum in each particular case, independently of having several solutions for one specific problem. The literature includes several studies, projects, designs and modes of behavior. In countries such as the United States, Japan and New Zealand, with more financial resources, many tests and studies have been undertaken in retrofitted structures and isolated repaired elements. During the middle of the 1980's, the Americans and the Japanese undertook a joint study, using large and reduced scale models which contributed to the profession with interesting research data and solutions. Several brilliant researchers from different universities and institutes were involved in these studies, as well as engineers from public offices and construction firms, which surely contributed with significant amounts of money to dwell deep into the studies. Also in Mexico, with less financial resources, but with a lot of ingenuity, other distinguished researchers have started tests and essays that proved the goodness and the advantages of the projects that the structural engineer experimented, projected and built. In this paper are presented some modest experiences that have been implemented in the professional practice, but which, to date, have provided adequate results, even if it is true that braced structures have not been subjected to an intense earthquake that has excited them beyond the elastic range.

Meeting the requirements and guidance of the regulations in force in everything referring to levels of stress and limitation of deformations, necessarily implied making a drastic and substantial modification of the building's structure. This had already been implemented in Mexico City before 1985. In 1979, after the so called "Ibero Earthquake", several buildings were retrofitted with steel diagonal shapes. Although in some cases the foundation was not modified, their behavior during the 1985 earthquake was specially satisfactory to the degree that maybe some of the buildings would have collapsed if they had not been braced. It is important to indicate that after the 1957 earthquake, structures were not modified as in 1979; the damaged elements were repaired and its sections were increased.

ANALYSIS DESIGN IN COMPLIANCE WITH STANDARDS

To comply and meet the standards with analysis and design, it is required, in principle, to detect and understand the dynamic behavior of the subsoil at the site and the same parameters about the structure. This should be done to modify the period of the building if possible, by pushing it away from the period of the soil at the site and thus prevent the retrofitted building from responding more to the action of the earthquake.

The first concept to be analyzed is the study of the behavior of the building, considering only the existing structure and defining the levels of stress and deformation in the case of the design earthquake. According to the results obtained, several proposals that meet the standards are make, and the results are compared to the allowable levels. The regulations send back to the beginning of the solutions, by requiring a verdict of structural stability and safety taking the following aspects into consideration:

a) That the retrofitted building attains the safety levels established for new structures.
b) To perform a careful inspection of the structural elements involved in the stiffness and resistance of the building.

c) To provide an accurate definition of the level of participation of the existing structure by means of an adequate diagnosis of the status of the building.
d) To prove that the existing structure possesses the adequate capacity to support vertical loads and 30% of the design horizontal forces before starting the retrofitting process.

One important part of the philosophy of the analysis and design to reinforce and stiffen structures, consists in visualizing the possible and future behavior of the structure under study. It becomes inadequate and antieconomic to analyze and design a new structure that will be capable of supporting the maximum horizontal forces that might occur. For this reason, it is a good idea to make an analysis and a congruent design with the characteristics, type and level of damage that the building had and with the estimated conditions of the possible design earthquake at the site. For these reasons the design should be made with the following criteria:

a) The building should be able to support small earthquakes without undergoing damages.
b) The building should be able to resist moderate earthquakes without any structural damage; some damages in the structural elements could be accepted.
c) Once analyzed and designed, the structure used for restructuring and stiffening should be capable of absorbing severe earthquakes without collapsing, even though damages in some structural elements could occur and some type of reinforcement in the areas affected can be later proposed.

A significant number of buildings or structures, which, without having been damaged, had to be stiffened, were analyzed and were designed with braced steel frames because there were major advantages, such as: less weight, ease of fabrication at the shop, simplicity in manufacturing and assembly, and simplicity in the connections, even though in some cases partial demolition or an increase in the number of connectors have to be used. Even so, there were many cases, that became complicated because of the absence of information about the existing structures or because of the difficulty of working in inhabited areas, in hospitals or telephone exchanges.

The system basically consists of placing steel braced frames connected to the existing structure that will absorb horizontal forces. The work of these frames is similar to the work of a large vertical truss.

The use of the system of steel braced frames may be performed both on the inside, as well as on the outside of the existing building.

MEETING THE REQUIREMENTS FOR ADEQUATE BEHAVIOR OF BOTH STRUCTURES, THE ORIGINAL AND THE NEW ONE

The fact of coupling two different structures is an important aspect that should not be neglected. This should be considered from the standpoint of analysis and design, even if it is true that the steel trusses or braced frames may attain large ductilities when working isolated. It should be remembered that when coupling two different structures made of different materials, usually concrete and steel, there are other factors involved: a different elasticity, several connection zones, uncertainties at the joints, difficulties in workability and labor because of the few spaces available, etc. All of this has taken to think of low seismic behavior factors, as to be able to absorb the existing uncertainties.

The construction regulations in force now in Mexico City, as well as the Complementary Technical Standards for Earthquake Design, consider these conditions and propose requirements that have to be met to select an adequate seismic behavior factor Q. A value of $Q = 2$ provides reasonable results, allows to work with tolerable safety ranges and does not generate unfavorable economic increments.

There is an important aspect between the interaction of both structures and that aspect is, to make an accurate assessment of the involvement of the floor system, and consider it as an undeformable horizontal diaphragm, which will guarantee the transmission of the shear forces to the new structure.

Special attention should be given to the careful inspection that must be made during the assembly stage between the existing building and the steel braced frame structure, because the stability of the building depends on it. Even though the analysis and design are studied and performed with the most modern methods and technologies, as with 3-D computer programs, if the coupling of both structures is not well solved, all the analysis and design performed are pointless.

To achieve good coupling, the basic thing is, and it is insisted on it, to think of the simplest possible condition of restructuring and stiffening, and apply the experience and good judgment of the engineer, as well as with the participation and good will of the architect and the owner.

CAREFUL STUDY OF THE CONNECTIONS AND MAKING THEM SIMPLE

All the paragraphs of this presentation are intimately interconnected among themselves, because with all of them, the ultimate goal of the study, which consists of the adequate reinforcement and stiffening of the structure, is achieved. Sections 3 (Adequate Behavior Between Both Structures), 4 (Careful Study of Connections) and 5 (To Synthesize Construction Problems), are the materialization and final achievement of the goal. But it is insisted on that no matter how good the execution and the design of the structure is made, if the connections of the proposed profiles can not be performed in a practical, simple and feasible way, nothing of what was done before has any meaning.

Therefore, in this paragraph it should also be mentioned that an important item, is the one concerning with connections.

Solving efficiently a connection in steel structures poses certain problems, mainly when orthogonal and diagonal members concur at the joint, and when the diagonal is the member that achieve the best efficiency for the system. Imagine now the complexity of the connection when it has to be placed between a new structure and an existing building, about which, in many cases, the internal characteristics are not known. It is here where it is really important to use ingenuity to propose the best type of joint and even so, many times, changes should be undertaken once the real conditions of the existing structure are known.

The connections have guaranteed that the stresses generated at the structure may be transmitted adequately.

Sometimes it is better to overdesign the connection, with the goal of dissipating, or at least minimizing the uncertainties, than to size them to the limit.

As a comment we will mention that the cost of a good connection is not very significant to the total cost of the retrofitting.

TO SYNTHESIZE CONSTRUCTION PROBLEMS MAINLY IN OCCUPIED BUILDINGS

In a good part of the retrofitting processes for damaged buildings, the construction processes are usually the ones that govern their feasibility.

5.a. The difficulty of work at the worksite.
5.b. The conditions of occupancy of the building.
5.c. The supply of materials to the worksite.
5.d. The little space available.

5.e. The high cost of the process.

These are a few of the items which force structural engineers to try, as much as possible, to minimize, synthesize and facilitate the construction aspects from the project and connection study standpoint.

The experiences that we have lived through in hospitals, schools and telephone exchanges were determinant to assess the importance of the topic. If we can have the presence of a construction engineer, a structure-fabrication engineer, both before and after the execution of the project and the design of the connections, many inconveniences that might arise during the construction stage can be prevented. The Builder and the Fabricator must contribute extremely valuable suggestions that should not be missed and which are extremely worthy of being taken into consideration. Not everything that is proposed may be the optimum, but the virtue of the project specialist is there, to know how to take advantage of and use, and benefit from the best available things.

On the other part, in occupied buildings, where it is impossible to have them evacuated, the presence of the users must define many of the conditions of the project and the design.

IN RETROFITTED BUILDINGS, OBTAIN THE INFORMATION TO KNOW THE POSSIBLE BEHAVIOR FOR THE FUTURE

Maybe the most relevant and most important item in retrofitted structures, independently of their construction feasibility, is the knowledge about future behavior. Since 1985 there has not been any earthquake in Mexico City which excites the structures in a way similar to what happened that year; even if it is true that there have been some earthquakes, they are all of them far away from what can truly be called trial by fire. Some Researchers and Scholars of Seismology predict an upcoming great earthquake. In fact the 1985 earthquake had been expected, coming from what is called the "Acapulco Trench", located East to the port. We know, through seismic histories, that this possible ground motion is dormant and is saving what might be a very sad surprise for us, given its closeness to Mexico City.

Because of all of this, it will be very important to know the information given to us by the behavior of the retrofitted structures. It is hoped that the predictions will obey the assumptions. If so; the instrumentation, the studies, the analyses, the careful design, the construction and the sufferings of the engineers will not have been in vain and Mexican Structural Engineering will be able to be proud of it.

CONCLUSIONS

The formulation of a careful study and identification of the problem, assessment of its true magnitude, a realistic analysis and design adequate to the type of structure and the level of the damage, adequate behavior of both structures by means of an optimal, simple and practical design of the connections, simplification of the construction processes, mainly in occupied buildings, will produce as a result, good behavior of the retrofitted structure for the benefit of the occupants, for the owner or owners and for the future of Mexican Engineering.

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