

Retrofitting existing reinforced concrete structures

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ABSTRACT: This paper presents the description of a method for evaluating existing reinforced concrete structures, particularly insofar as resistance to earthquakes is concerned, with suggestions regarding reinforcement when necessary.

The decision as to whether to leave the structure as is, reinforce it or demolish it will be based on application of this method, together with other relevant studies (economic, investment opportunity, functional, etc.).

INTRODUCTION

A given occurrence, such as a fire, an earthquake, a strong wind, an accidental action or any other occurrence that causes deterioration in a building; changes in city zoning, a drop in profitability, a change of use, or simply functional, aesthetic or economic obsolescence are all factors which, either jointly or individually, can lead to the need to adapt or fit out the building so that it can provide the service required. Sometimes a mere change in technology or in the criteria for evaluating the safety or efficiency of buildings, in the form of mandatory standards, is enough to make retrofitting advisable, or even mandatory.

This paper presents a method that has been developed and improved in actual cases in which successful solutions were found. This method covers experience and thought given to the subject, as well as data received from other professionals, from authors and institutions that have worked in this field.

We must, however, stress the multidisciplinary nature of retrofitting work; this is necessary to deal properly with the many variables involved in the problem.

METHOD PROPOSED

The method consists of the following stages:

- 1 Gathering of information
- 2 Qualitative evaluation
- 3 Analytical evaluation

2.1 Gathering of information

This stage calls for:

a) Documentary information that can be consulted: Reports, soil studies, blueprints, structural calculations, materials testing, construction ledgers, inspection reports, history of services and maintenance of the building, etc.

b) Inspection of the site to compare the documentary information and the actual building, which means checking to see that it was built according to the plans, detecting changes that affect the structure, looking into possible damage due to accidental loads (earthquakes or wind) or any other cause, assessing the physical condition of the structure and evaluating the quality of maintenance in general.

c) If the information gleaned from the aforementioned activities is not sufficient, a request can be made for supplementary information, which can consist of destructive or nondestructive testing to determine the quality of the materials used in the building, verification measurements, inspection of structural and non-structural elements and supplementary verification of soil conditions and the foundation system.

The choice of the most appropriate type of evaluation will depend on the quality and amount of information gathered.

In the specific case of essential structures, classified as Group A structures (Ref. 3, article 5.1), such as schools, hospitals, fire stations, police stations, government buildings, historical monuments, etc., given the importance of the buildings, the choice

between destructive or non-destructive testing to determine the strength characteristics of the materials in the existing structure are not optional. In this case the tests must be performed to more accurately determine the characteristics of the materials that affect structural behavior.

2.2 Qualitative evaluation

This is a comparison between the information available concerning the characteristics of the existing building and the general guidelines of the expected behavior; it is used to determine whether or not a diagnosis of the building is possible. The steps to be followed are:

a) Critical analysis of the information gathered, based on the updated information available concerning overall behavior of reinforced concrete structures, supplemented by the knowledge of the professional performing the evaluation. The general design principles to be evaluated would include, among others, the age of the building, the strength of the materials used, the design, detailing and construction, the quality control and construction techniques, the superstructure's load bearing system, the configuration both in plan and on elevation, the infrastructure system, separation from neighboring buildings, the presence of rigid elements not considered in the analysis, the detection of damage that occurred before the evaluation and the physical condition of the building.

b) Following completion of the general analysis described in the preceding paragraph, the possible structural deficiencies could be rated; to do so, it is advisable to prepare an evaluation matrix that would show the damage index applicable to the superstructure. See Table 1.

Based on the information available and the results of the general analysis of the building, the values of the different structural aspects considered most significant are entered in the matrix. Each value will be within a range from 0 to 1, depending on the level of vulnerability assigned to each. These values, as shown in the matrix form, are then multiplied by a weight factor to take into account the importance of each in the overall behavior of the structure.

This provides the partial vulnerabilities for each aspect which, when added together, show the vulnerability of the superstructure.

c) Application of factors related with the soil type to the damage index.

Once the evaluation matrix has been applied and the building's vulnerability index has been determined, the influence which the underlying soil has on the damage index is considered.

To determine the amplification factors of the damage index, it is necessary to use the following soil classification system, which is based on depth of rock, the characteristics of the strata and the topography of the land on which the building is located. This information will be taken from the geotechnical studies available.

For this, soil profiles are divided into 4 types: S1, S2, S3 and S4. Profiles S1, S2 and S3 are the same as defined in Covenin-Mindur standard 1756-80-82, chapter 6. Profile S4 is for soils where the liquefaction potential has been suppressed or diminished.

As for the topography of the land, there are three representative configurations that influence the damage index, namely: flat, on a slope, on a slope with landfill.

The damage index amplification factors associated with soil profile (F1) and topography (F2) are shown in the following tables:

soil profile	amplification factor F1
S1	1.0
S2	1.2
S3	1.5
S4	2.0

topography	amplification factor F2
flat	1.0
on a slope	1.5
on a slope with landfill	2.0

The damage index (DI) will be calculated with the formula:

$$DI = V * F1 * F2 \quad (\text{Eq. 1})$$

where V = vulnerability of the building, based on the evaluation matrix, and F1 and F2 are the values obtained from the previous tables.

d) Use of the damage index to make the final diagnosis of the qualitative evaluation.

To make the diagnosis, the damage index variation range will be applied as shown below:

Variation range (DI)	Diagnosis
0.0 - 0.2	leave as is
0.2 - 0.4	reinforce (without additional analysis)
0.4 - 0.8	reinforce (with additional analysis)
0.8 or higher	demolish

If, in the opinion of the professional in charge of the study, a diagnosis of the building can be made based on the qualitative evaluation described above, the options would be to leave the building as is, reinforce it or demolish it, taking into account other specialties having a bearing on the study.

If a diagnosis of the building cannot be made, an analytical evaluation, as described below, will follow.

In the case of essential structures, as defined above, the information provided by this qualitative evaluation is not thorough enough for a reliable diagnosis. Therefore, in cases involving this type of building, it is necessary to move directly on to an analytical evaluation, skipping the qualitative evaluation.

2.3 Analytical evaluation

The analytical evaluation can be defined as a study of the building's strength, stiffness and strain capacity, using manual or computerized analytical procedures.

The purpose of this evaluation is to quantify the seismic capacity ratio of the building being studied, which is defined as the quotient of the existing building's seismic capacity and that required by current seismic standards for new buildings.

The analytical evaluation consists of the following steps:

a) Reducing the existing structure to a theoretical model that can be analyzed with the computational procedures available.

b) Determining the dynamic characteristics of the

existing structure using the methods provided for in the current regulations or experimental procedures such as ambient vibration or forced harmonic vibration by counter-rotating mass actuator.

c) Choosing the response reduction factor on the basis of the existing detailing.

d) Determining the elastic design spectrum for the design earthquake appropriate for the area where the building is located.

e) Determining the permanent design loads (self weight, dead weight, etc.), variable ones (overloads, rheological, etc.) and accidental ones (earthquakes, wind, etc.), using the current standards.

f) Processing the data described above using the proper analysis tools for the case in question in order to determine the overall strain and strength requirements.

g) Interpreting the results of the analysis and obtaining the data needed to calculate the seismic capacity ratio (Scr). This ratio is given by the following equation:

$$Scr = \sum Ce/Rsn \quad (Eq. 2)$$

$$\text{where, } Ce = Rc - (f1 * PL + f2 * VL) \quad (Eq. 3)$$

and Ce = seismic capacity of the element; Cr = real capacity of the element; f1 and f2, load factors set in the current standards; PL = permanent loads; VL = variable loads and Rsn = seismic force required by regulations.

The Scr should be calculated for shears, moments, axial loads and relative lateral displacements. If it is > 1, the building meets the strength, stiffness and lateral displacement standards and will not need reinforcement. If Scr is < 1, the options are:

Range of Scr variation	Option
0.7 - 1	Minor reinforcement
0.4 - 0.7	Major reinforcement
0.1 - 0.4	Demolish

If reinforcement is required, it will be based on the applicable criteria and the types of deficiencies found.

This reinforcement will cause a change in the conditions of the structure being analyzed; therefore, the changes must be incorporated in the structural model and the latter must again be analyzed. This

process must be repeated until $Scr > 1$ is achieved.

If the analytical evaluation shows that the building must be demolished, specific investment conditions would be one of the aspects taken into account.

Once the last stage of this method, in other words the qualitative and/or analytical evaluation, has been completed, a diagnosis of the building may be made.

3 REINFORCEMENT

3.1 General criteria

Any reinforcement of a building must be based at least on the following general criteria:

a) Structural: Avoidance of unnecessary masses, favoring symmetry in the plan and elevation, use of continuous and hyperstatic structural systems, endowing the system with the stiffness necessary to avoid non-structural damage during moderate or frequent earthquakes, avoidance of sharp variations in strength, stiffness and ductility, use of "strong column - weak beam" designs, appropriate detailing of the load bearing elements, designing the infrastructure to absorb the loads from the superstructure and designing the elements bearing in mind the possibility of damage.

b) Architectural:

Functional: distribution, rating and relation of spaces, heights, dimensions of the elements, location of the non-structural elements, pedestrian and vehicular traffic, etc.

Aesthetic: volume, finishing, height, lighting, etc.

Urban development: regulations in force for the zone (area limitation, withdrawal, facade height, etc.), pedestrian and vehicular traffic, aesthetic relations, climate, topography, etc.

c) Construction: Choice of construction materials available in the zone, proposing construction techniques that can be performed by labor and technological infrastructure that are easily found, coordinating development of the reinforcement project with related aspects of other systems (plumbing, electric, mechanical) and masonry work.

d) Economic: The reinforcement project must meet preestablished economic feasibility limits.

3.2 Reinforcement techniques

1) In the case of a minor reinforcement, the techniques to be used, without further analysis, would include, among others: improving the distribution and anchoring of non-structural elements and increasing the confinement reinforcement in the existing columns and/or walls.

2) In the case of a major reinforcement, the options would be:

a) Increasing the strength and stiffness by filling spaces along existing lines of resistance or by creating new ones. There are three possible methods:

Reinforced concrete additions using materials of the same or better quality than those used in the existing structure. Walls poured on site or prefabricated walls, increasing sections of existing walls and columns (casing), etc.

Structural steel additions: adding frames and bracing; increasing sections of existing elements, etc.

Additions of reinforced masonry bearing walls.

b) Increasing the ductility, either by adding transversal reinforcement or electrically welded mesh around the element; or using metal casing; placing steel angles in the corners of columns, held in place by grills, clamps, etc.

c) Increasing the stiffness, strength and ductility by using a combination of the techniques described above.

As for the infrastructure, if the case involves minor reinforcement, there would be no alteration in the existing foundations.

If, however, major reinforcement is required, the following situations might arise:

1) If the current loads on the infrastructure are not increased by more than 7.5%, the existing system is enough.

2) If they will increase by more than 7.5%, reinforcement of the foundations will depend on the strength characteristics of the underlying soil and the structural system chosen for reinforcement. The most commonly used reinforcement techniques are: increasing the footing shoe section, creating a foundation slab, adding deep foundations (piles or minipiles), etc.

The reinforcement stage marks the end of the retrofitting job. A strict inspection system must be established for the construction stage, since a good project is not enough and unforeseen situations may arise which require analysis and on-the-spot decisions.

Furthermore, proper treatment of a building requires a good maintenance system and periodic evaluations.

REFERENCES

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3. Covenin-Mindur 1756-80-82. Norma Venezolana. Edificaciones antisísmicas. Venezuela. Page 67.
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QUALITATIVE EVALUATION MATRIX

Aspect	Characteristic	Vulnerab. Range	Assigned Vulnerab. (1)	Weight Factor (2)	Partial Vulnerab. (1) x (2)
AGE	before 1967	0.5-1.0		0.05	
	1967 - 1983	0.3-0.5			
	after 1983	0.0-0.3			
DETAILING	bad	0.5-1.0		0.075	
	regular	0.2-0.5			
	good	0.0-0.2			
CONSTRUCTION	bad	0.5-1.0		0.075	
	regular	0.2-0.5			
	good	0.0-0.2			
LOAD BEARING SYSTEM	inadequate	0.4-1.0		0.10	
	regular	0.2-0.4			
	adequate	0.0-0.2			
AMOUNT OF COLUMNS &/ OR WALLS	low	0.5-1.0		0.10	
	medium	0.2-0.5			
	normal	0.0-0.2			
DISTRIBUTION OF MASS & STIFFNESS	not balanced	0.5-1.0		0.075	
	intermediate	0.2-0.5			
	balanced	0.0-0.2			
PLAN DISTRIBUTION	asymmetrical	0.5-1.0		0.075	
	intermediate	0.1-0.5			
	symmetrical	0.0-0.1			
IRREGULARITIES	soft ground	0.0-1.0		0.05	
	short columns	0.0-1.0		0.0375	
	discont. diaph.	0.0-1.0		0.0375	
FOUNDATIONS	inadequate	0.3-1.0		0.075	
	dequate	0.0-0.3			

Aspect	Characteristic	Vulnerab. Range	Assigned Vulnerab. (1)	Weight Factor (2)	Partial Vulnerab. (1) x (2)
DISTRIBU- TION NON- STRUCTURAL ELEMENTS	asymmetrical	0.3-1.0		0.0375	
	intermediate	0.1-0.3			
	symmetrical	0.0-0.1			
NEIGHBOR- ING BUILD- INGSfar	close	0.4-1.0			
		0.10			
		0.0			
PREVIOUS DAMAGE	columns	0.7-1.0		0.075	
	beams	0.3-0.7			
	floor struct.	0.2-0.3			
	masonry	0.0-0.2			
MAINTENANCE	poor	0.5-1.0		0.0375	
	regular	0.1-0.5			
	good	0.0-0.1			
				Vulnerability (V) Σ	-----