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# Optimization of the Rehabilitation of Concrete Buildings Based on Their Dynamic Properties

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***Authors' contributions***

*This work was carried out in collaboration between all authors. Author JHR designed the study and managed the scope of numerical analysis. Author IC wrote the protocol and wrote the first draft of the manuscript. Authors LPR and TLL revised the manuscript and managed the numerical test. Authors JHR and ERG revised the manuscript and managed the literature searches. All authors read and approved the final manuscript.*

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## ABSTRACT

The present work describes the development of an optimization model for the rehabilitation process of concrete buildings damaged mainly by the effects of an earthquake. Currently, the process is carried out according to the current standards and the damage assessment is based largely on visual damage, which can obviate internal damage to the elements of the structure which cannot be detected at a glance and which will affect its behavior in the future. By means of a non-linear optimization process, the optimization of the modal analysis of concrete buildings has been carried out by means of steel or concrete jacketing in order to reduce the increase in weight generated by these new elements. When analyzing the results it can be observed how increasing the quantity of elements to be repaired increases the complexity to obtain a combination of sections that while keeping the increase in weight to a minimum does not negatively affect its fundamental frequency.

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## 1. INTRODUCTION

Repairing a concrete building damaged by an earthquake is not an easy task. This requires a review of the mechanical behavior of the structure due to inelastic deformations, cracks, deflections and other visible damage suffered by the elements [1]. The evaluation of these damages is at the discretion of the engineer deciding as well to consider the contribution of the damaged structure in conjunction with the rehabilitation elements.

The damage can be particularly severe when the dominant frequency of the earthquake approaches the resonant frequency of the structure. Standard repair procedures tend to cause a change in the mass and rigidity of the structure which leads to two major problems: a weight gain that was not considered when designing the foundation and potential changes in the natural frequency of the structure which will change the response of the building to a future dynamic excitation.

Mexico is one of the countries in the world with the highest seismic activity. According to statistical data, there are more than 90 earthquakes per year with magnitude greater than 4 degrees on the Richter scale, which is equivalent to 6 percent of all earthquakes recorded in the world. During the 20th century, high-intensity earthquakes occurred in each of the decades that caused considerable material damage and the number of deaths [2].

On September 19 and 20, 1985, two earthquakes of great intensity occurred, which caused serious damage and losses in part of the Mexican territory, especially in the metropolitan area of its capital.

The earthquake of September 19 had a magnitude of 7.8 (shortwave, MS) and 8.1 (long wave, MW) on the Richter scale. The amplitude of the waves of the initial earthquake was between 3 and 5 times greater than anticipated, without the cause being known in detail and lasted between 2.5 and 3 minutes. The next day's earthquake was 7.3 Richter degrees and completed the break of the old union between Cocos plates and North America [3].

According to the National Center for Disaster Prevention (CENAPRED for its acronym in Spanish), the damage extended from the west coast to the central plateau of the Republic, although the most serious were concentrated in a relatively small radius, especially in the Federal District. The latter is explained by a combination of factors, including the fact that many buildings especially those between 8 and 15 stories high-came into resonance due to the long duration of the earthquake. The resonance of the soils mainly those located in the center of the Valley of Mexico where there are lacustrine deposits-coincided with the frequency of the waves of the earthquake since the anti-seismic construction standards in force provided much lower amplitudes than those actually they happened. Multifamily and office buildings between eight and fifteen floors, hotels, hospitals and schools collapsed or became unusable. Only in large-scale buildings did the official count reach around 3,300 damaged buildings. Some 36,000 homes were destroyed and more than 65,000 experienced significant damage [3].

On September 7 of 2017, an 8.2 magnitude earthquake occurred in the Gulf of Tehuantepec, 133 km southwest of Pijijiapan, Chiapas. The earthquake, which occurred at 23:49:18 hours, was felt in the south and center of the country and caused heavy damage on the Isthmus of Tehuantepec. This earthquake presented a large number of aftershocks, many of which could not be located due to their small magnitudes. The number of replicas until September 30 was 5791, two of them of magnitude 6.1 [4].

On September 19, 2017, the National Seismological Service (SSN) reported an earthquake with magnitude 7.1 located on the state boundary between the states of Puebla and Morelos, 12 km southeast of Axochiapan, Morelos and 120 km from Mexico City [5].

The decision on how to repair the structure is often made by conducting an inspection according to applicable regulations in the workplace; these are usually based on observable damage and not on a detailed analysis of the damaged members which may cause details to be ignored and for these to impact on its structural behavior in the future.

The different methods of repair for different elements present in the structure can lead to an increase in the total mass damaged building generating a greater force of inertia in response to a future earthquake making ineffective repair procedures performed in addition to the effect of extra weight on the foundation of the building which was not contemplated at the time of designing it.

Depending on the state of the structure after the seismic event, the National Center for Disaster Prevention (CENAPRED) classifies the types of structural damage in the following way [1]:

Non-structural damage: As its name says, it is the damage suffered by those elements that do not have any structural function in the construction, they only fulfill functions that do not affect the seismic-resistant behavior of the structure, such as the decorative ones frequently used in colorful facades, the dividing walls that are very usual in structures based on frames, an element that has the insulating function, or all kinds of glassware.

Light structural damage: It affects the structural elements that intervene in the seismic-resistant capacity of the structure. In a practical way, it is identified by the appearance of cracks smaller than 0.5 mm in width in the concrete elements, as well as the fissures and falls of flattened walls and roof. Even when the structural elements have suffered damage, there is no reduction in the earthquake-resistant capacity of the structure, as well as non-structural damage there is no need to vacate the structure, only the restoration of the damaged elements is enough to repair it.

Strong structural damage: These damages in the structural elements are of consideration, they are located when there are cracks of 0.5 mm to 1.0 mm wide in the structural elements of concrete. Given the importance of damage to the structure, there is a considerable reduction in seismic-resistant capacity. Due to the damage, damaged elements must be propped up immediately, resulting in controlled access to the property.

Severe structural damage: It is the most critical state that can suffer the structure, are located cracks of more than 1.0 mm in width in concrete elements, the detachment of the coating in columns, the crushing of concrete (Fig. 1), the breakage of stirrups and the buckling of the Reinforcement in columns as in concrete wall, cracking of flat slabs around the columns, the collapse in columns of more than 1: 100 of its height and the collapse of the building of more than 1: 100 of its height.

**Fig. 1. Shear failures of columns [6]**

The rehabilitation systems that can be applied to each particular case will depend on the characteristics of the structure and the problems it presents (insufficient resistant capacity, low rigidity, inadequate ductility, etc.).

In the seismic rehabilitation of structures, the lateral resistance is often provided by the modification and/or addition of elements only in certain parts of the structure like in the case of jacketing of these elements with either steel (Fig. 2) or concrete (Fig. 3). The remaining elements of the structure are usually not reinforced.

**Fig. 2. Steel jacketing of a column [7]**

Through the use of an unconstrained sequential minimization technique (SUMT) in conjunction with modal dynamic analysis, this paper aims to develop a methodological procedure that will optimize the weight of a concrete structure and lead to the choice of appropriate repair techniques without deriving in deficient dynamic conditions allowing to propose conditions under which a building could be efficiently repaired.

**Fig. 3. Concrete jacketing of columns and beams [8]**

## 1.1 Background

Jirsa [8] wrote about the challenges in the seismic rehabilitation of structures after the 1985 earthquake in Mexico City. Table 1 summarizes information on 379 buildings that partially or completely collapsed or were severely damaged during the 1985 earthquake [9]. The buildings are listed according to the structural type and the number of stories. Concrete buildings represent 86% of the total, 47% were built between 1957 and 1976, and 21% were built after 1976. The damage was concentrated in buildings with 6 to 15 floors and most of these buildings are medium height were concrete structures.

The main failure modes observed in the 1985 earthquake are listed in Table 2. The results were obtained from a survey of 331 buildings in the most affected area of Mexico City that represented the most severely damaged or collapsed buildings [10].

Horta-Rangel et al. [11] studied how the change in the mass of the elements damaged by seismic actions after their repair produces a change in their natural vibration frequencies, seeking to obtain a desirable range for these frequencies in the that the rehabilitation process can be optimal. To find the optimal design, a modal analysis was carried out using the ANSYS software considering an optimization model based on the weight of the structure and its natural frequencies. It was concluded that the increase in mass in the columns lower part of the building increases the natural frequency.

**Table 1. Record of damage to buildings that occurred during the 1985 earthquake in Mexico City. This record is a function of the number of floors and the material of the buildings**

| Type of structure | Extent of damage | Number of stories | | | | Total |
|---|---|---|---|---|---|---|
| | | <5 | 6-10 | 11-15 | >15 | |
| R/C Frames | Collapse | 37 | 47 | 9 | 0 | 93 |
| | Severe | 23 | 62 | 14 | 0 | 99 |
| R/C Frames | Collapse | 0 | 1 | 0 | 1 | 2 |
| and shear walls | Severe | 2 | 1 | 2 | 0 | 5 |
| Waffle slab | Collapse | 20 | 31 | 6 | 1 | 58 |
| | Severe | 6 | 33 | 19 | 0 | 58 |
| Waffle slab | Collapse | 0 | 0 | 0 | 0 | 0 |
| and Shear Walls | Severe | 0 | 2 | 3 | 0 | 5 |
| R/C Frames | Collapse | 3 | 0 | 0 | 2 | 5 |
| and Beam-Block Slab | Severe | 0 | 1 | 2 | 1 | 4 |
| Steel Frames | Collapse | 6 | 1 | 3 | 3 | 13 |
| | Severe | 0 | 2 | 1 | 0 | 3 |
| Masonry Bearing Walls | Collapse | 8 | 0 | 1 | 0 | 9 |
| | Severe | 19 | 1 | 1 | 0 | 21 |
| Masonry Bearing Walls | Collapse | 1 | 0 | 0 | 0 | 1 |
| with R/C Frames | Severe | 3 | 1 | 0 | 0 | 4 |
| Total | | 128 | 183 | 61 | 7 | 379 |

**Table 2. Types of faults in buildings damaged by the 1985 earthquake in Mexico City**

| 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 | 20.5 |

### 1.2 Modal Analysis

The corresponding equation based on the linear elastic behavior of a non-damped system is:

$$([\mathrm{K}] - \omega_n^2[M])\{\phi_n\} = 0 \tag{1}$$

Where:

[K] is the stiffness matrix
$\omega_n^2$ is the natural frequency squared
[M] is the mass matrix
$\{\phi_n\}$ is the vector of vibration modes

This has nontrivial roots when:

$$\det([\mathrm{K}] - \omega_n^2[M]) = 0 \tag{2}$$

By expanding the determinant we obtain a polynomial of order N in $\omega^2$. Equation (2) is known as the characteristic equation or frequency equation. This equation has N real and positive roots for $\omega^2$, which determine the N natural frequencies of vibration [12].

## 2. METHODOLOGY

### 2.1 Record of Damage to Buildings in the World Due to an Earthquake

The Earthquake Engineering Research Institute of the United States makes available to the public a database with information on the damage caused by earthquakes in buildings around the world through the website concretecoalition.org, among which are both steel buildings and of concrete, when choosing a specific building known or found by means of its search engine we will obtain all the available information of this about the original configuration of the building, materials used in its construction, sections and foundations, as well as the damages observed, if this was demolished or had repaired and in that case to have it of what type was.

### 2.2 Optimal Procedure

Most problems of structural optimization involve the minimum of an objective function of design variables subject to a set of constraints which are of the geometric and behavioral type. The constraints which stem from limitations on stresses, displacements and the allowable member sizes are implicit functions of the design variables and are often highly nonlinear.

Perhaps one of the easiest ways of solving such a nonlinearly constrained problem is the penalty method. In this method, an auxiliary objective function, which is a function of the original objective function, and the constraints are constructed.

In the context of the interior penalty method, the algorithm that is most commonly used is the Sequential Unconstrained Minimization Technique (SUMT) proposed by Fiacco AV, et al. [13]. The algorithm involves the use of a sequence of penalty parameters which converts the constrained problem into a sequence of unconstrained problems using the last solution as the initial guess for the next unconstrained problem.

A non-linear optimization method coupled with the modal analysis of the structure was performed.

The Z function representing the weight of the structure is minimized with respect to the design variables $x_i$. The restrictions of Z are generally given in the form of inequities and associated with the state equations (design equations). The optimization model can be written as follows:

$$\min Z = f(x_1, x_2, x_3, \ldots, x_n) \tag{3}$$

Such that:

$$a_1 \le x_1 \le a_2 ; a_3 \le x_2 \le a_4 \ldots a_{r-1} \le x_n \le a_r \tag{4}$$

$x_i$ = design variable corresponds to the additional thickness of the sections.
$a_i$= assigned value.

The state variables will be the frequencies (Freq). The range of values $f_1$, $f_2$ depends on the frequency change required.

$$f_1 \leq Freq \leq f_2 \quad (5)$$

The objective function Z represents the total weight of the structure, being proportional to the volume V of this. Therefore, the Z function can be expressed as follows:

$$Z = \rho g V \quad (6)$$

Where ρ corresponds to the density of the concrete and g is the gravitational acceleration.

Getting the minimum V guarantees the minimum of Z, so;

$$Min Z \alpha Min V. \quad (7)$$

Volume V will involve the variables that affect the weight of the structure; for the case of jacketing, we have as variables the thickness that will be increased to the sections of the elements in the structures:

ESC1 = Minimum thickness of the jacket of the columns.
ESC2 = Maximum thickness of the jacket of the columns.
ESB1 = Minimum thickness of the jacketing of the beams.
ESB2 = Maximum thickness of the jacketing of the beams.

The restrictions imposed on the state and design variables will be:

ESC1 ≤ ESC ≤ ESC2
ESB1 ≤ ESB ≤ ESB2
f1 ≤ Freq ≤ f2

Where:

ESC = Thickness of the jacket in columns by story
ESB = Thickness of the lining in bars by story
Freq = Fundamental frequency.

Fig. 4 presents the above procedure through a flow chart.

### 2.3 Regarding the Modeling of the Jacketing Elements

When modeling the jacketing using ANSYS, we chose a hollow box element with a uniform thickness on all four faces (Fig. 5), the rectangular element of the original element is no longer considered for the analysis, only its contribution to the total weight of the repaired building is taken into account.

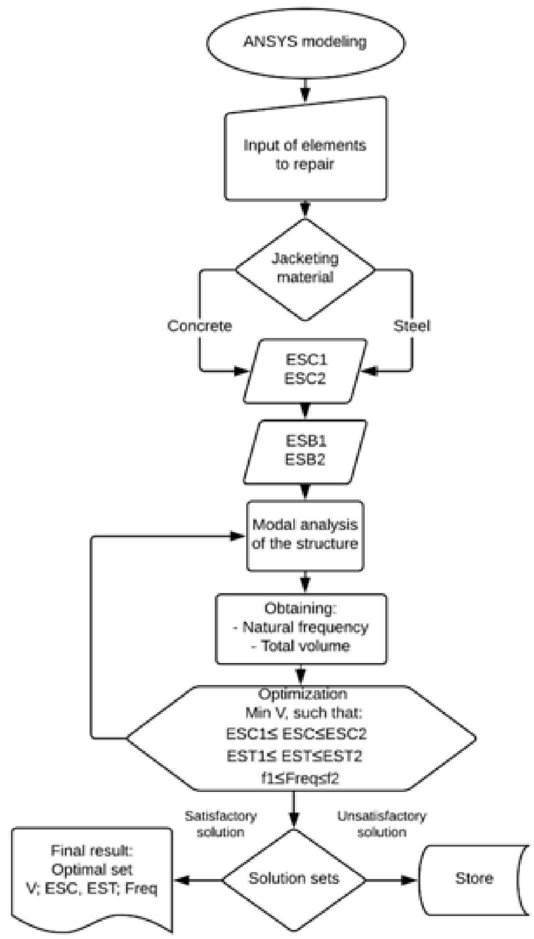


**Fig. 4. Flowchart of the optimization procedure**

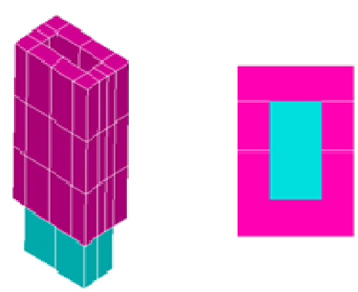

**Fig. 5. Jacketing: Isometric view and cross-section**

## 3. RESULTS AND DISCUSSION

The analysis of the rehabilitation of concrete buildings with different characteristics in terms of height as well as regularity was carried out, analyzing in each case the options for jacketing both concrete and steel.

It was observed in cases where repairs are necessary on the ground floor (Fig. 6) that the fundamental frequency was reduced in most iterations as well as an appreciably constant behavior of how much less weight is added to the major structure is this reduction in frequency, both for steel and concrete jacketings (Fig. 7). In the case of buildings where the height is exceeded considerably by its length (Fig. 8) it was observed that for concrete jacketing there is a tendency to increase the fundamental frequency (Fig. 9).

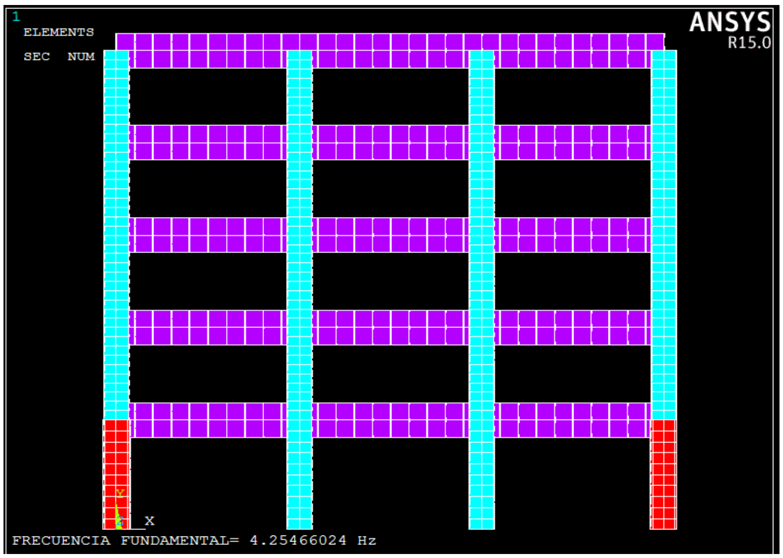


**Fig. 6. Five-story building with damage in the first story**

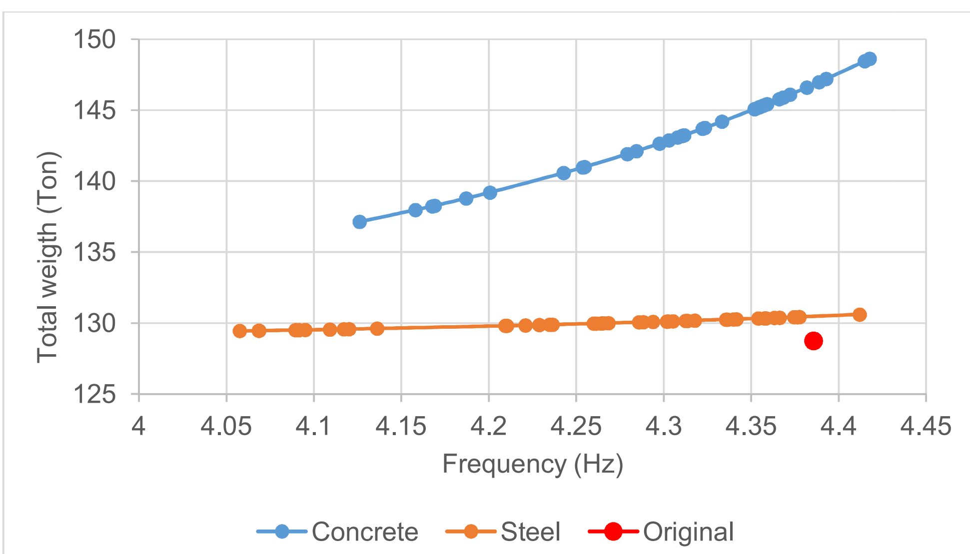


**Fig. 7. Variation of the weight of the rehabilitated Five-story building with respect to its resonance frequencies. The Damage occurs on the first story. Case1: Reinforcement concrete jacketing, case 2: Reinforcement Steel jacketing, case 3: No additional reinforcement**

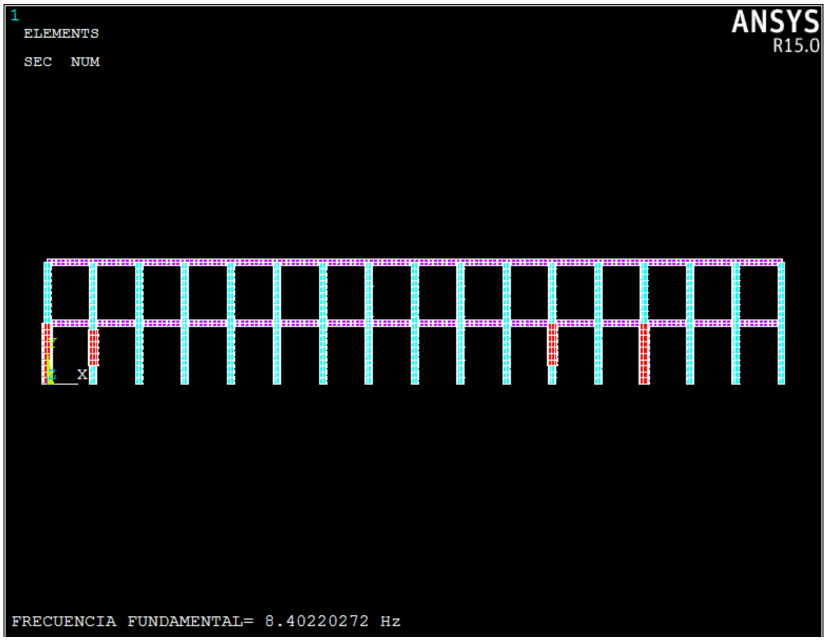


**Fig. 8. Two-story building with damage in the first story**

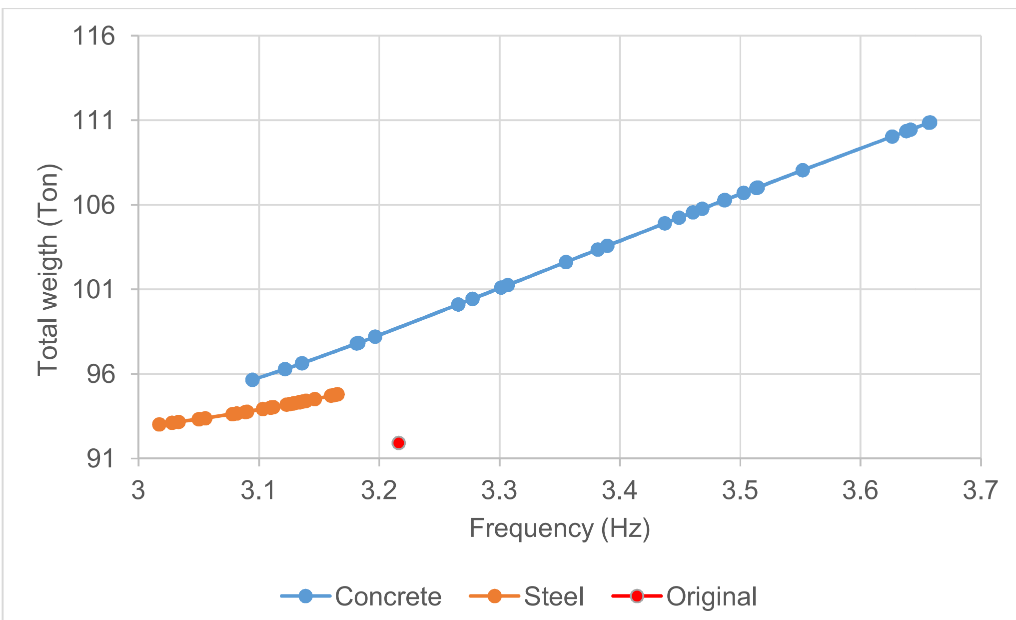


**Fig. 9. Variation of the weight of the rehabilitated Two-story building with respect to its resonance frequencies. The Damage occurs on the first story. Case1: Reinforcement concrete jacketing, case 2: Reinforcement Steel jacketing, case 3: No additional reinforcement**

When the repair must be done at the top of the column as a capital (Fig. 10) the end result always derives the increase of the fundamental frequency this increased stiffness gained by the jacket (Fig. 11).

In buildings of medium height and with irregular geometry (Fig. 12), it can be seen how, for a greater number of elements to be repaired, the results become more dispersed (Fig. 13) allowing to appreciate the operation of the algorithm, in this case the steel jacketing will increase the fundamental frequency while at each iteration it offers considerably smaller than the weight of the concrete jacketing, which has the optimal solution with a natural frequency closest to the original.

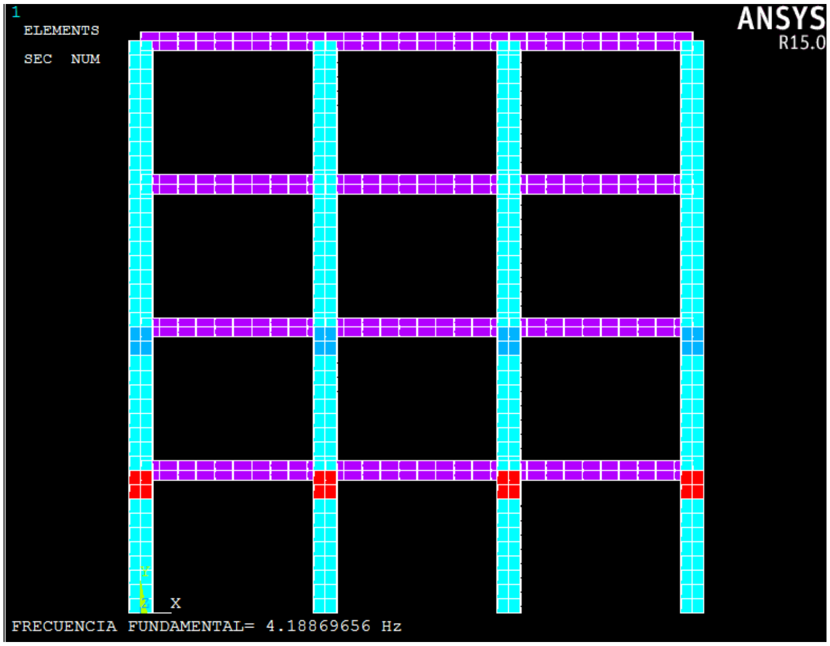


**Fig. 10. Four-story building with damages in the first two stories**

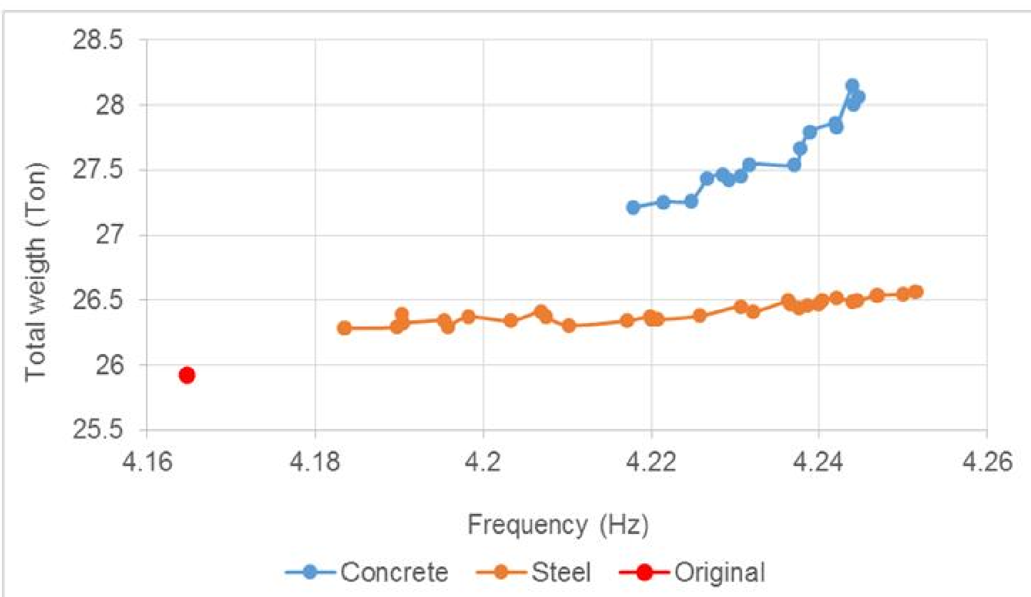


**Fig. 11. Variation of the weight of the rehabilitated Four-story building with respect to its resonance frequencies. The Damage occurs on the first two stories. Case1: Reinforcement concrete jacketing, case 2: Reinforcement Steel jacketing, case 3: No additional reinforcement**

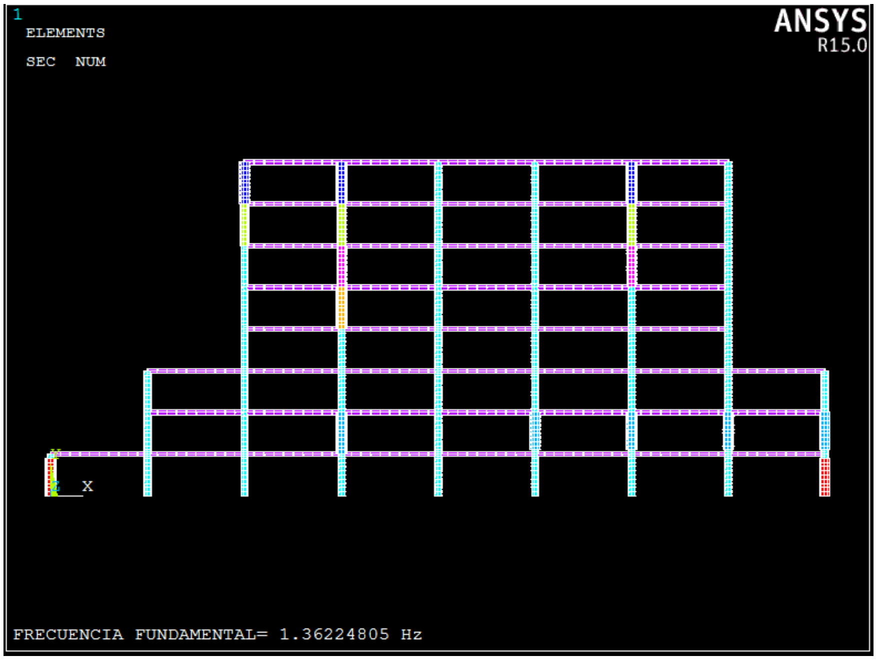


**Fig. 12. Eight-story building with damage in six of its stories**

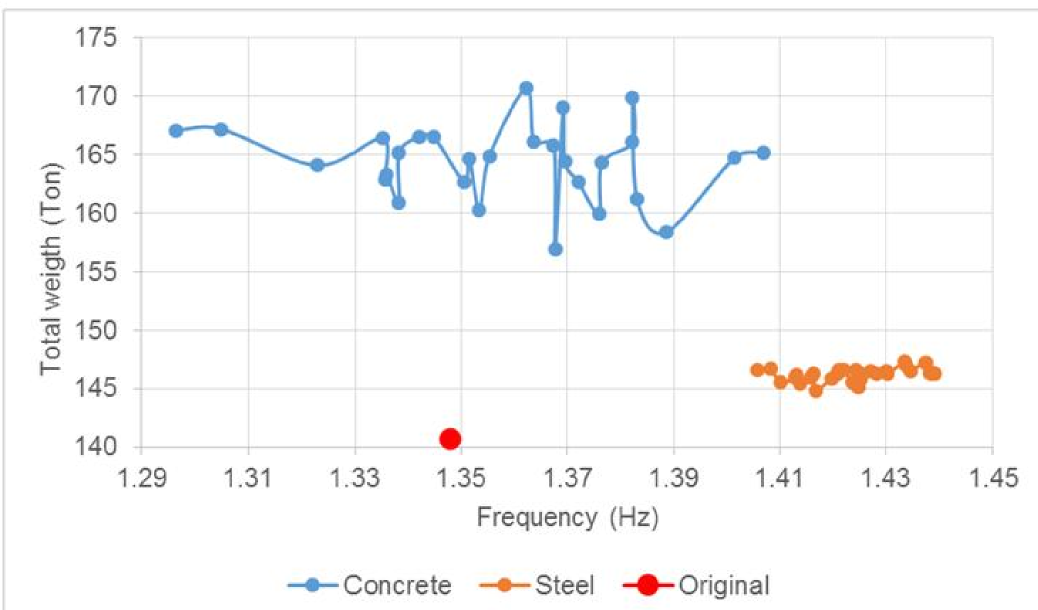


**Fig. 13. Variation of the weight of the rehabilitated Eight-story building with respect to its resonance frequencies. The Damage occurs on six of its stories. Case1: Reinforcement concrete jacketing, case 2: Reinforcement Steel jacketing, case 3: No additional reinforcement**

For buildings over 13 floors and of regular geometry (Fig. 14) it is observed how the repair in the lower floors does not have great effect on the frequency even though the weight increase for the steel jacketing is less than 2% of the original weight of the structure much less than 8% of the approximate increase of the concrete jacketing (Fig. 15).

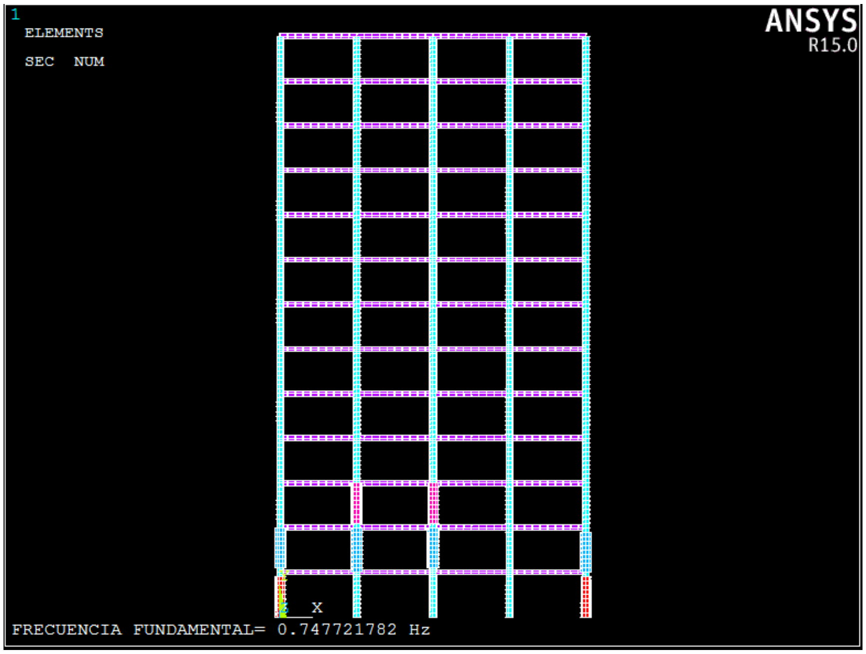


**Fig. 14. 13-story building with damage on the four first stories**

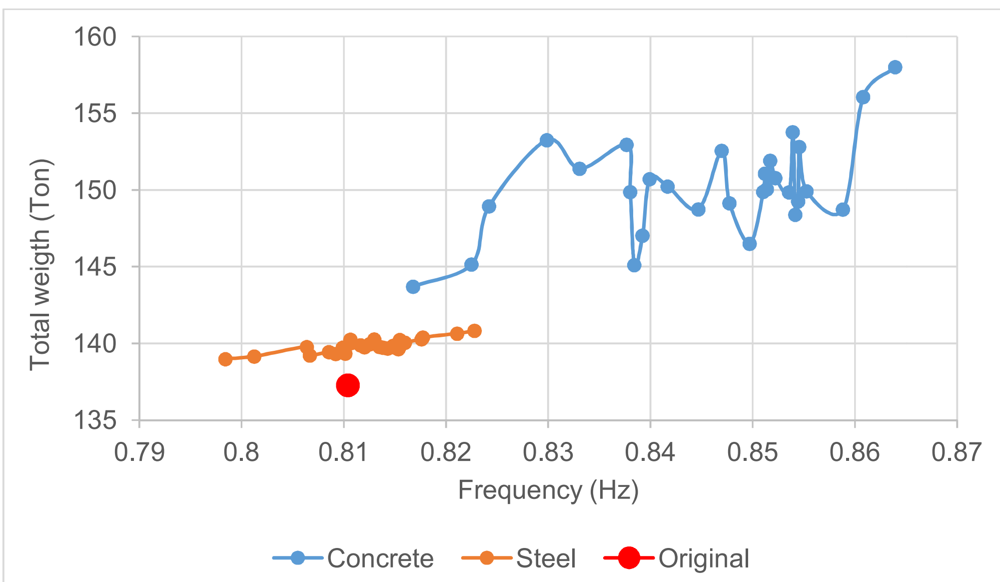


**Fig. 15. Variation of the weight of the rehabilitated 13-story building with respect to its resonance frequencies. The Damage occurs on the four first stories. Case1: Reinforcement concrete jacketing, case 2: Reinforcement Steel jacketing, case 3: No additional reinforcement**

If the building has irregular geometry (Fig. 16) and with elements to be repaired distributed over a large part of the building, in both cases the natural frequency was reduced while the weight of the steel jacket did not vary greatly (see Fig. 17), for the different sets of the concrete jacketing a variation of up to 9 tons of difference between the minimum and the maximum is observed.

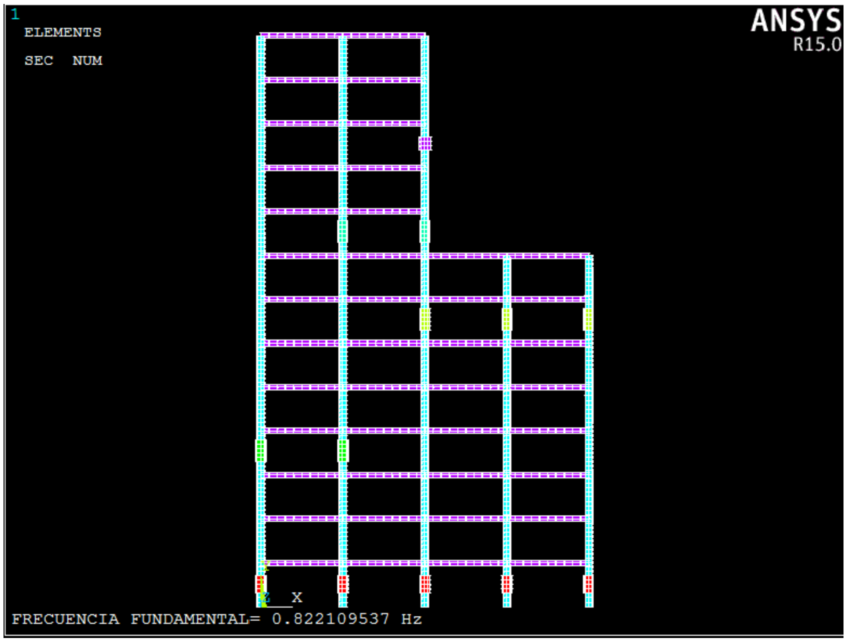


**Fig. 16. 13-story building with damage in four of its stories**

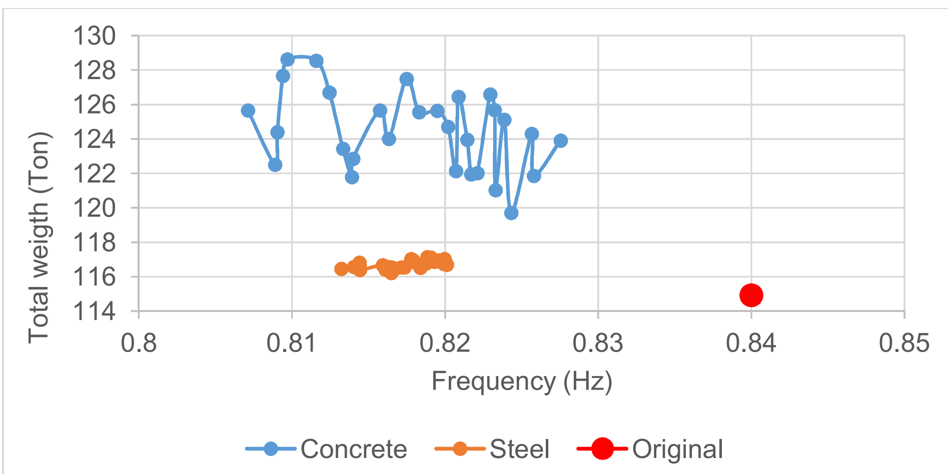


**Fig. 17. Variation of the weight of the rehabilitated 13-story non-regular building with respect to its resonance frequencies. The Damage occurs on the four first stories. Case1: Reinforcement concrete jacketing, case 2: Reinforcement Steel jacketing, case 3: No additional reinforcement**

## 4. CONCLUSION

Although the concrete and steel jackets are traditional techniques, there is greater certainty about the use of these when considering how they work considering the contribution to the rigidity of the damaged element as null compared to materials such as carbon fiber. By not being able to ensure the behavior of the damaged element, we must make sure that it works properly. Reducing the added weight when carrying out the rehabilitation of the structure will reduce, as far as possible, the future collateral damage that the foundation could suffer because this addition was not considered at the time of design.

The optimization process undoubtedly allows us to evaluate a wide range of possible combinations when choosing the repair elements of damaged sections, giving the possibility to obtain a basis to choose how to rehabilitate a building by joining the conditions in situ as the hand of work and the time available for execution.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

## REFERENCES

1. Takeshi J. Norma for the evaluation of the damage level by earthquake in structures and technical rehabilitation guide (reinforced concrete structures). National Center for Disaster Prevention. Mexico; 1996.
2. Ordaz M. Modifying circular 54/12 of the insurance company. Official Journal of the Federation. National Insurance and Finance Commission; 2012.
3. Bitrán D, Acosta L, Eslava H, Gutierrez Z, Salas M. Characteristics of the socioeconomic impact of the main disasters that occurred in Mexico in the period 1980-99. National Disaster Prevention Center and Secretariat of Governance. Mexico; 2001.
4. Working Group of the National Seismological Service, UNAM. Earthquake Report: Earthquake of September 07, 2017, Chiapas (M 8.2). National Seismological Service; 2017.
   Available:http://www.ssn.unam.mx/sismicidad/reportes-especiales/2017/SSNMX_rep_esp_20170907_Chiapas_M84.pdf
5. Working Group of the National Seismological Service, UNAM. Earthquake Report: Earthquake of September 19, 2017, Puebla-Morelos (M 7.1). National Seismological Service; 2017.
   Available:http://www.ssn.unam.mx/sismicidad/reportes-especiales/2017/SSNMX_rep_esp_20170919_Puebla-Morelos_M71.pdf
6. Fardis MN. Seismic design, assessment and retrofitting of concrete buildings: Based on EN- Eurocode 8. Springer, Dordrecht; 2009.
7. Aboutaha R, Engelhardt MD, Jirsa JO, Kreger ME. Seismic Retrofit of R / C columns using steel jackets, ACI SP-160. Seismic Rehabilitation of Concrete Structures. 1996;59-72.
8. Jirsa, James O. Challenges in seismic rehabilitation of structures. Earthquake Engineering Challenges and Trends J.J. Pérez Gavilán (Editor), Instituto de Ingenieria, UNAM, México; 2005.
9. Iglesias J, Aguilar J. Identification of damages caused by the earthquakes of 1985, 1979 and 1957 in the Metropolitan Area, Seismicity Studies in the Valley of Mexico, 3rd Part, Chapter III, Annexes I and II, Department of the Federal District and United Nations Center for Human Settlements (HABITAT), Mexico, DF; 1998.
10. Meli R. Evaluation of performance of concrete buildings damaged by the September 19, 1985 Mexico Earthquake; The Mexico Earthquakes-1985: Factors Involved and Lessons Learned, ASCE. 1987;308-327.
11. Horta J, Carmona S, Castaño VM. Shift of natural frequencies in earthquake-damaged structures: An optimization approach. Struct. Surv. 2008;26:400–410. Available:http://www.emeraldinsight.com/10.1108/02630800810922748
12. Chopra A. Dynamics of structures. Pearson Education, Mexico. 2014;407-408.
13. Fiacco AV, McCormick GP. Extensions of SUMT for nonlinear programming: Equality constraints and extrapolation. Management Sci. 1966;12:816-829.



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