

# STUDY ON SEISMIC EVALUATION AND RETROFITTING OF A FIVE-STORY REINFORCED CONCRETE BUILDING IN EL SALVADOR

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## ABSTRACT

The current seismic code in El Salvador does not consider any regulations, methodologies, or guidelines related to the seismic evaluation and retrofitting of existing buildings. El Salvador is a country with high seismicity. Many earthquakes have occurred in the past and caused extensive damage and losses, affecting numerous people. Therefore, it is important to implement methodologies and tools to improve the performance of existing buildings against natural disasters.

One of the main issues is the construction cost of retrofit strategies. This study focuses on identifying cost-effective retrofit strategies for a reinforced concrete (RC) building in El Salvador and compares this strategy with a detailed seismic evaluation method (DSE) against a typical retrofitting strategy (RC jacketing) designed using the typical design practice in El Salvador.

Three retrofit plans (steel bracing, RC wall, and Ferrocement Lamination [FCL] wall) were evaluated based on the construction cost and characteristics of each retrofit technique, and an optimal and cost-effective retrofitting strategy was proposed. A comparison of the two methodologies highlights the advantages of using the detailed seismic evaluation method outlined in the HOKYO Project Manuals. This method combines non-linear analysis criteria from American standards with the seismic index from Japanese standards. By doing so, the required shear strength of each story to meet seismic demands can be determined. Consequently, this approach optimizes design and reduces construction costs.

**Keywords:** Detailed seismic evaluation, construction cost, retrofit, reinforced concrete building.

## 1. INTRODUCTION

El Salvador has suffered many natural disasters, particularly earthquakes, causing significant damage and losses. In 1986 a big earthquake occurred, after this the current seismic code (Technical Standard for Seismic Design of El Salvador [NTDS-97]) was proposed and in 2021, a new seismic code began to be developed, these do not include regulations, guidelines or an official methodology of how to evaluate and retrofit existing buildings; however, the common practice is to follow the methodologies presented in the NTDS-97 for new buildings (the equivalent lateral force and response spectrum analysis), these methodologies does not consider the nonlinear behavior of structural elements. In the metropolitan area of San Salvador, there are many public and private buildings constructed before NTDS-97, In addition, the owners sometimes intend to change the original use of the buildings, which could increase the seismic demand due to the importance factor for the specific use and likely do not meet the seismic demand for this new use, and it is necessary to propose a retrofit plan for these buildings; however, owing to the lack of knowledge on how to design different retrofit techniques and the unawareness of the construction cost, the structural designers proposed expensive solutions, causing the owners to lose motivation to retrofit existing buildings. From 2022, the Planning Office of the Metropolitan Area of San Salvador (OPAMSS) and Japan International Cooperation Agency (JICA) have been working on

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the HOKYO project, the main aim is to reduce the seismic vulnerability of buildings through manuals and guides. One methodology presented in the evaluation manual is the Detailed Seismic Evaluation (DSE), proposed by Nakajima et al., 2020. This study provides structural designers with a clear understanding of the construction costs of different retrofit techniques applied in a medium-rise building and the benefits of applying the DSE method in comparison with the common practice in El Salvador.

## 2. DATA

The case study building is a five-story reinforced concrete building, which is an office building in El Salvador, where the ground level is used as parking, and the upper floors are used as office space. The typical height of each floor is 3030 mm (Figure 1). The structural system consists of RC frames in both directions. Figure 2 and Figure 3 show the structural elements. Table 1 summarizes the building's information and Figure 4 shows the seismic demand based on NTDS-97.

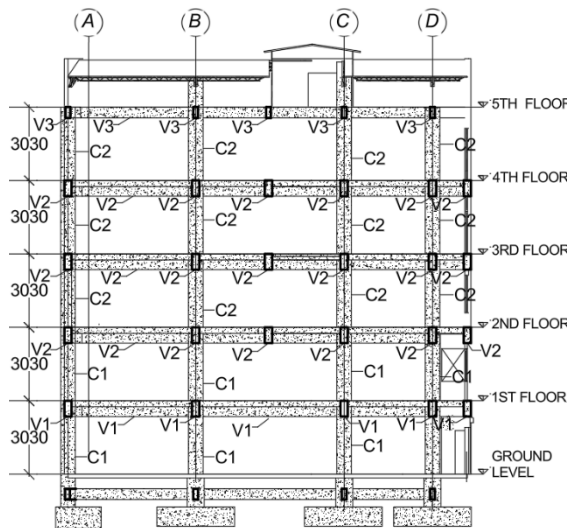


Figure 1. Typical structural section (unit: mm).

Table 1. Target Building Information.

Items	Information/Data
Location	San Salvador, El Salvador
Proposed Use	Office Building
Structural type	Reinforced concrete frame
Number of stories	5-five
Occupancy category	II (table 3 NTDS-97)
Importance factor	1.2 (table 4 NTDS-97, special occupancy buildings)
Soil type	S3 (table 2 NTDS-97)
Concrete strength	27 (MPa)
Expected Yielding strength	280 (MPa)
Total Seismic weight	10,381.35 (kN)
Total height	15.15 (m)

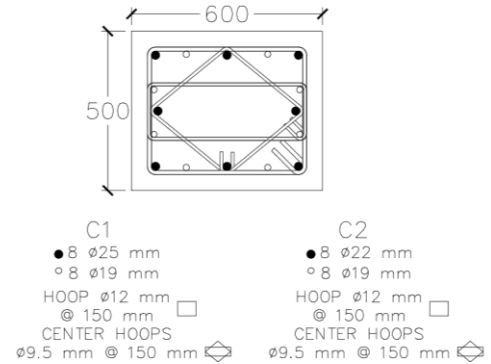


Figure 2. Columns of the target building.

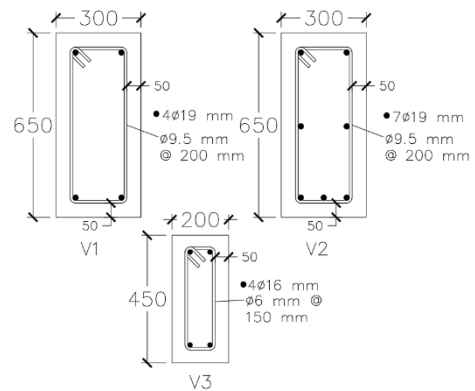


Figure 3. Beams of the target building.

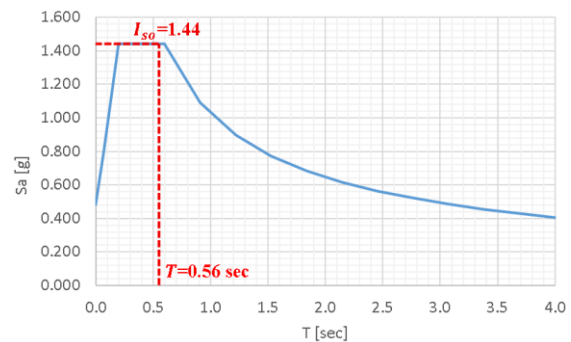


Figure 4. Target Seismic Index Iso.

### 3. METHODOLOGY

#### 3.1. Seismic evaluation of the existing building

The methodology of this study was conducted in accordance with the process illustrated in the flowchart provided in Figure 5. The first step was to select an existing five-story reinforced concrete building with a predefined retrofit plan (RC jacketing) designed following the unofficial standard practice commonly used in El Salvador. After that, the target seismic index ( $I_{SO}$ ) was calculated based on the response spectrum defined in the NTDS-97 and the fundamental period of the building, followed by the seismic evaluation of the existing building, to obtain the seismic index ( $I_S$ ) of each story, conducted following the DSE method using the ETABS software, considering only the bare frame. This method consists of carrying out a pushover analysis considering the criteria presented in the Seismic Evaluation and Retrofit of Existing Buildings, American Society of Civil Engineers (ASCE 41-13). After this, instead of obtaining the capacity curve of an equivalent single Degree of Freedom (SDOF) model, the capacity curve of each story was obtained to calculate the strength index (C) and the ductility index (F). In this study, the F index of 2.0 obtained in the HOKYO project experiment was used. Finally, following the procedure described in the Japan Building Disaster Prevention Association manual (JBDPA), the  $I_S$  for each story was obtained and subsequently compared with the  $I_{SO}$ . Figure 11 and Table 4 show the results; consequently, it was necessary to propose a retrofitting plan in each story.

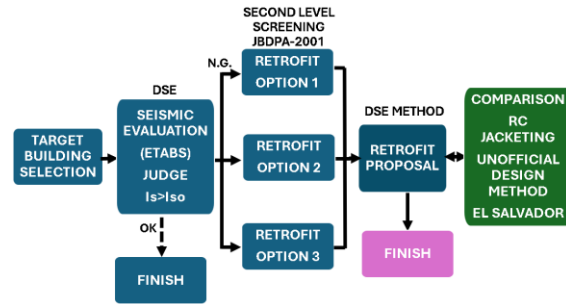


Figure 5. Methodology flowchart.

#### 3.2. Retrofit options

In this study, three retrofitting plans were implemented. Table 2 summarizes the different techniques implemented in each option. The second-level screening procedure and the guidelines established in the JBDPA manual and the manual for ferrocement lamination retrofit (Seki et al., 2024) were followed to design and evaluate these retrofit options, and the construction cost of each retrofit option was calculated. A comparison among all the retrofit options was conducted, and based on this comparison, the final retrofit strategy was proposed (Retrofit proposal) using a combination of RC walls (used for the lower stories) and FCL walls (used for the upper stories), and the corresponding construction cost was estimated. Additionally, the construction costs of the predefined retrofitting design (RC jacketing) and of a new office building, with the same floor area and number of stories, were calculated. Finally, a comparison was made.

Table 2. Used Retrofit elements in each

Opt. 1 (steel bracing)	Opt. 2 (RC wall)	Opt. 3 (FCL wall)
HSS 150X150X6	RC wall t=200 double $\phi 9.5 @ 150$	FLC wall t=200
HSS 200X200X6	RC wall t=200 double $\phi 12 @ 150$	FLC wall t=250
HSS 250X250X6	RC wall t=250 double $\phi 16 @ 150$	

#### 3.3. Restraining analysis using ETABS software

When a pushover analysis is conducted with ETABS, it is not possible to obtain the complete strength capacity of the upper stories (Figure 6 and Figure 7). As shown in Figure 6, the collapse prevention (CP) point occurs first in the shear wall on the fourth story, preventing the elements on the fifth story from reaching the CP point and obtaining the maximum capacity in that story. However, in this study, some simplifications were applied to obtain them. This involves restraining the columns in the upper part of one story before the story under analysis (Figure 8). By applying the restraining analysis and increasing

the capacity of the restrained story (Figure 8), the CP point occurred first in the shear wall of the fifth story. Figure 9 shows the ultimate shear capacity in this story.

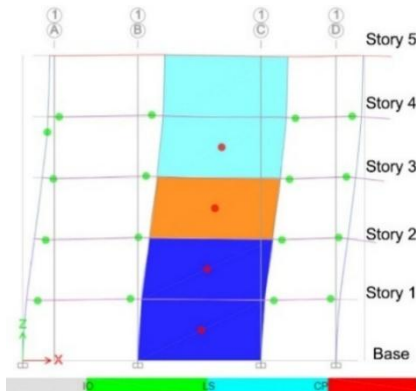


Figure 6. Hinge response at story 5

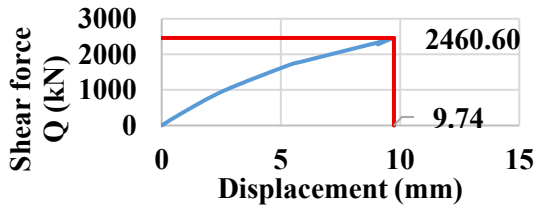


Figure 7. Q vs Displacement curve for the fifth story, whole building pushover analysis.

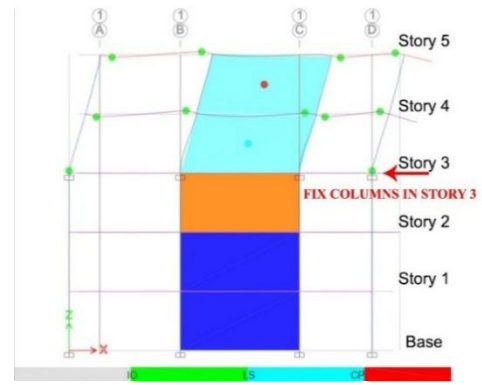


Figure 8. Hinge response at the fifth story, restraining analysis.

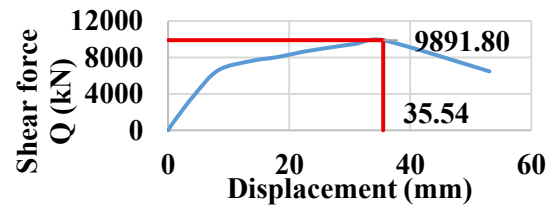


Figure 9. Q vs Displacement curve for the fifth story, restraining pushover analysis.

direction. Shell elements were used to model the RC walls, and strut elements were implemented to model FCL walls. These types of retrofits were modeled in ETABS. First, the F index was defined for each element based on the HOKYO experiments, with a rotation angle equivalent to 1/150. For this value, the corresponding F index is 1.27.

### 3.4. Analysis of retrofit proposal using the DSE

The DSE was conducted to evaluate the retrofit proposal. Table 3 and Figure 10 summarize the distribution of the retrofit elements in X- and Y-directions.

Table 3. Retrofit proposal for the target building.

Story	Retrofit Technique (X-dir)	qty
5	FCL Wall t=200	2
4	FCL Wall t=200	2
3	RC Wall t=200 $\phi$ 12 @150	2
2	RC Wall t=250 $\phi$ 16 @150	2
1	RC Wall t=250 $\phi$ 16 @150	2
Story	Retrofit Technique (Y-dir)	qty
5	FCL Wall t=200	2
4	RC Wall t=200 $\phi$ 9.5 @150	2
3	RC Wall t=200 $\phi$ 12 @150	2
2	RC Wall t=250 $\phi$ 16 @150	2
1	RC Wall t=250 $\phi$ 16 @150	2

The restraining analysis was conducted to obtain the capacity curves of the fifth story, in X- and Y-directions.



Figure 10. Distribution of the walls.

#### 4. RESULTS AND DISCUSSION

Figure 11 shows the shear force  $Q$  vs displacement in the X- and Y-direction for the existing building. The curves show the maximum value of the shear capacity of each story, and after the ultimate point (UP) line, based on the hinge response of the elements and the trend of each curve, it will not significantly increase. These shear forces were used to calculate the seismic index of each story (Table 4). Figure 14 shows that the  $I_s$  of each story in both directions was less than the target seismic index  $I_{SO}$ .

Table 4. Seismic evaluation results of the existing building.

STORY	Q (kN)	$I_s$	$I_{SO}$	Judgment
<b>X-direction</b>				
5	2947.96	<b>0.44</b>	1.44	<b>N.G.</b>
4	2697.09	<b>0.52</b>	1.44	<b>N.G.</b>
3	2155.39	<b>0.52</b>	1.44	<b>N.G.</b>
2	1361.62	<b>0.51</b>	1.44	<b>N.G.</b>
1	303.26	<b>0.51</b>	1.44	<b>N.G.</b>
<b>Y-direction</b>				
5	2771.35	<b>0.41</b>	1.44	<b>N.G.</b>
4	2535.50	<b>0.48</b>	1.44	<b>N.G.</b>
3	2026.25	<b>0.49</b>	1.44	<b>N.G.</b>
2	1280.04	<b>0.48</b>	1.44	<b>N.G.</b>
1	285.09	<b>0.48</b>	1.44	<b>N.G.</b>

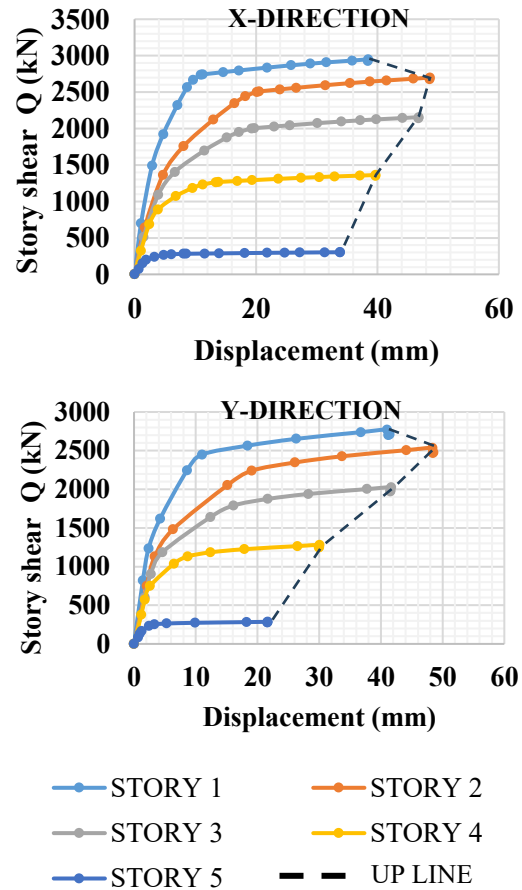


Figure 11. Q vs disp. curves X- and Y-direction, respectively, of the existing building.

The shear force  $Q$  vs displacement curves of each story in the X- and Y-direction after applying the retrofit proposal (RC and FCL walls) are presented in Figure 12. After the UP line is reached, a reduction in the capacity of each story is presented. The shear forces in the UP points were used to calculate the  $I_s$ . Figure 14 shows the results of the  $I_s$  of each story after retrofitting in the X and Y-direction. The results show that the seismic index values are greater than the target seismic index  $I_{SO}$ .

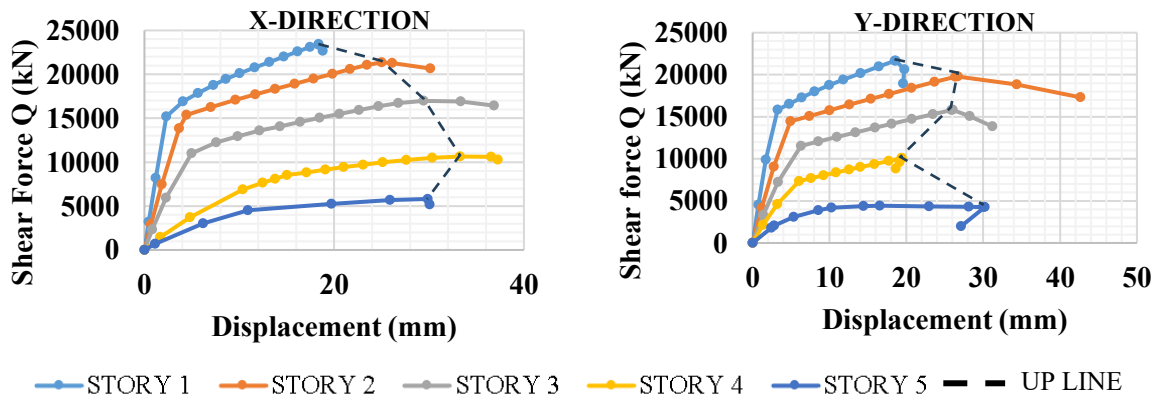


Figure 12. Q vs disp. curves X- and Y-direction, respectively, retrofit proposal, restraining analysis for story 5.

Figure 13 shows the construction cost comparison between the proposed retrofit (RC + FCL walls), the predefined retrofit plan (RC jacketing), and the construction costs of a similar new office building. If a retrofit plan is applied to an existing building, a reduction in construction costs is evident compared to a new building. In the case of the predefined retrofit plan (RC jacketing), the construction cost is 67% less than the cost of a new office building. However, in the case of the retrofit proposal designed following the DSE method, the construction cost is approximately 76% less than the cost of the RC jacketing retrofit plan following the common practice in El Salvador, and 92% less than the new building construction cost.

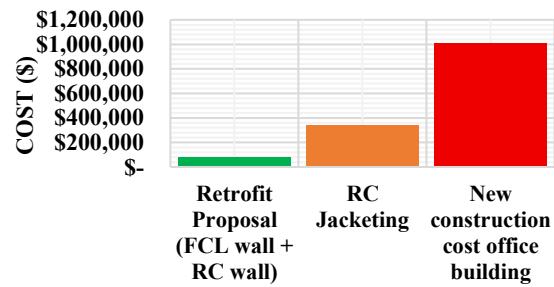


Figure 13. Construction costs comparison.

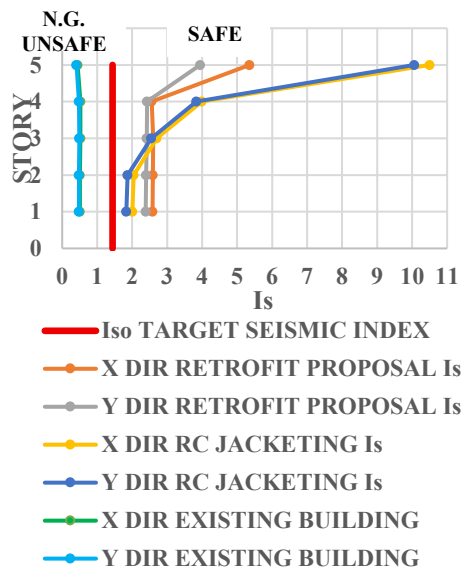


Figure 14. Comparison of seismic index of the existing building, retrofit proposal, and RC jacketing.

In this study, to gain a better understanding and make a comparison, the seismic index for the retrofit plan (RC jacketing) designed by the structural engineering consulting office, following the common practice in El Salvador, was calculated using the DSE method (Figure 14). It can be observed that the seismic index of each story for both retrofit plans meets the target seismic index; however, on stories 4 and 5, the value of the seismic index for the RC jacketing is markedly greater than the values for the retrofit proposal, which indicates an overdesign in retrofitting.

## 5. CONCLUSIONS

The DSE method is a valuable tool for evaluating and designing the retrofit of existing buildings. It considers the nonlinear behavior of the structural elements and allows for obtaining the seismic capacity of each story and determining the required shear strength to meet the seismic demand, which is useful for optimizing the design and reducing the construction costs.

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