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Optimal Methods for Retrofitting Corrosion-Damaged Reinforced Concrete Columns

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Abstract

By neglecting optimization criteria, engineers can articulate different views with respect to retrofitting a column for a particular bending moment and axial load for columns deteriorated by corrosion, especially those in a salt factory where they are exposed to chloride ions. In this study, ETABS and MATLAB softwares were applied to develop an optimal plan that involves minimal repair costs and maximum safety. To determine the specifics of this optimal plan, it needs to consider all variable parameters, including externally bonded steel plates, different types of concrete jacketing, and various concrete compressive strengths. By stabilizing implemented loadings and building's dimensions, 30 retrofitting designs are identified for consideration with respect to the two retrofitting methods to identify their effects on structural component design, sustainability, and economics.

A comparison of two retrofitting methods reveals that the use of each retrofitting method would be effective under certain circumstances. However, in this study, externally bonded steel plates appear to be more effective for the type of construction problems identified. In addition, the results indicate that the consideration of safety factors in the corroded structure to obtain optimal retrofitting can exert dramatic effects on the parameters involved in the process. Therefore, all variables are carefully analyzed in this study.

Keywords: Corroded column, retrofitting, concrete structures, externally bonded steel plates, concrete jacketing.

1 Introduction

Reinforced concrete (RC) rehabilitation is considered to be one of important aspects of the RC construction. In fact, repaired and strengthened designs of RC column are usually based on the assessment of engineers whose expertise can have an important role in the decision-making process. Along with structural design failures of concrete columns, the corrosion of the reinforcements is the most important cause of concrete deterioration. Consequently, they affect the serviceability, load carrying capacity, and safety of the reinforced concrete structures (Montemor, Simoes, & Ferreira,

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2003; Pantazopoulou & Papoulia, 2001; Rodriguez, Ortega, & Garcia, 1994; Vu & Stewart, 2000). During the past decades, various practical and analytical models have been proposed to predict the cost and service life of the composite concrete structures and estimate the remaining life of concrete bridge, their physical mechanism and mathematical model in order to predict the concrete cover cracking (Banerjee & Shinozuka, 2008; Cusson, Lounis, & Daigle, 2010; Eskandari & Korouzhdeh, 2016). These researches can help to identify the corrosion percentage and capacity reduction of RC columns. However, all available retrofitting and repairing methods of concrete structures should be identified for a structure with low loading capacity in order to select the most suitable approach. But for rehabilitation and retrofitting of this reduced capacity, it has to be to known, the various retrofitting and repairing methods for concrete structures (Bazaez & Dusicka, 2016; BouSiaS, 2009; Hollaway, 2011; Kalogeropoulos, Tsonos, Konstandinidis, & Tsetines, 2016; Ronagh & Eslami, 2013; Zeinoddini & Dabiri, 2013). Since retrofitting methods aim to obtain the original mechanical properties of the structure, it is highly recommended to study the force-moment interaction diagram of structures in details. Usually columns are subjected to a combination of axial compression, P, and bending moments, Mx and My, induced by unbalanced moments at connecting beams, vertical misalignments, or lateral forces resulting from dynamic loads. From the practical point of view, the RC column is performed by means of P–M interaction diagrams. This interaction diagram has been applied to many structures such as fire-exposed reinforced concrete sections (El-Fitiany & Youssef, 2014; Law & Gillie, 2010), heated concrete sections (Caldas, Sousa, & Fakury, 2010), mortars for different cement types (Nunes, Oliveira, Coutinho, & Figueiras, 2009), FRP-confined reinforced concrete columns (Rocca, Galati, & Nanni, 2009), and RC interaction diagram codes (Korn, 1974). Carpinteri et al. (Carpinteri, Corrado, Goso, & Paggi, 2012) studied the size-scale effects on reinforced concrete columns by means of the numerical approach to compute the P–M interaction diagrams which is well established in the design of reinforced concrete columns. This model can predict the size and the confinement effects, according to the experimental results. According to another research, different practical aspects such as (Júlio, Branco, & Silva, 2003) anchoring and slab crossing of the added longitudinal reinforcement and spacing of stirrups and addition of new technology concrete should be taken into account when reinforced concrete jacketing of columns were used to assess the strengthening and rehabilitation. As mentioned before, there are several aspects of applying various materials to retrofit the corroded RC structures. However, there is little available information about the process/result and insufficient code guidelines for optimization of the designs and methods to retrofit corrosion damages of reinforced concrete columns.

2 Significance of the Research

The aim of this research is to provide a method for the construction of a simplified interaction P-M diagram for RC columns for retrofitting the practical design applications. Based on ETABS and MATLAB coding, the proposed method aims to analyze the various but equivalent specimens in conventional RC columns by considering appropriate axial force–bending moment interactions for RC column with the minimum cost. However, for a particular axial force and bending moment, there is only one economical design type, which means only for a certain percentage of reinforcement of the designed concrete and retrofitting accessories, the column is optimized.

Main objectives of the present work are as follows:

- To optimize the reinforcement process considering the costs of concrete and reinforcement.
- To compare the column costs for various concrete strengths (Fc) as well as types of retrofitting methods.

3 Case Study Frame Modeling and Gravity Load Effects

The case study structure consists of a five-floor salt factory in which modeling and analyzing are conducted by ETABS building analysis (CSI, 2005). Fig. 1 shows the entire modeled structure.

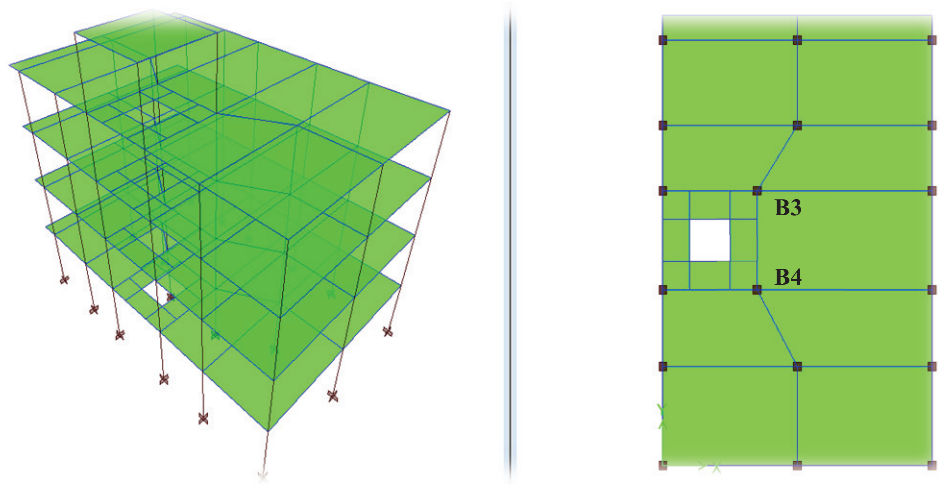

Figure 1: ETABS model of five-floor salt factory.

The frame element is capable of replicating the effects of axial and biaxial shear deformations as well as biaxial bending and torsion (CSI, 2005).The mentioned assumption is considered for analysis in the early designs. The loads of 260, 200 kg/m^2 have been applied as dead and live loads to the floors respectively. The upper 80-ton salt tank storage is located right in the center of four columns that means each column has 20 tons to bear. After five years, the capacity of each element reduces about %50 due to corrosion. ETABS is used to analyze both corroded and initial frames. In addition, two methods of retrofitting with various properties of materials are introduced to this damaged structure and the P-M interaction diagrams are obtained for all the situations. Moreover, the output data shows that the columns B3 and B4 in Fig. 1 are the critical columns. Owing to this fact, cost optimization along with safe design based on the P-M interactions is applied to B3 as one of the mentioned critical columns.

4 Retrofitting methods

4.1 Externally-Bonded the Steel Plates

One of the RC columns retrofitting procedure is done by external bonding of steel plates which can improve the performance of concrete columns. The effectiveness of this method depends on the hardness of the steel plates in lateral deformation of the RC column. To implement the retrofitting, the steel plates are closed all over the column and small space will open to be filled up by concrete which may increase the shear strength of column. Use a circular steel plate on investment is much more difficult than other coating methods, but research shows that this method of increasing resistance and displacement of inelastic column and is very effective (Karimi, Tait, & El-Dakhakhni, 2011).
Fig. 2 shows the schematic face of this method in since failure of this type will be on the patched areas of the conventional longitudinal reinforcement in columns; it could be more effective to use long steel plates to reduce the probability failure of the flexural longitudinal reinforcement.

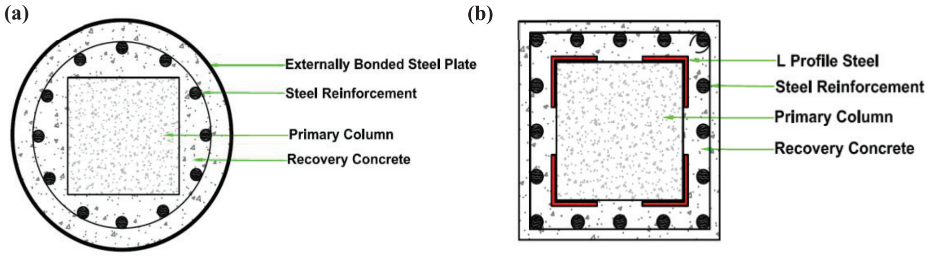

Figure 2: Retrofitted RC Column by (a) externally-bonded steel plate and (b) concrete jacketing considering L Profile.

The formulae used here for define the section of column was introduced by ACI 318 (Committee, Institute, & Standardization, 2008) for determining dimension and steel bars of concrete columns. The ultimate axial load capacity of the concrete section must be checked to make sure concrete column can support loads. Failure in the longitudinal reinforcement of patch such failure is ordinary in the column. The use of steel coverage to reduce the probability of failure of longitudinal reinforcement patch increases performance bending patch of column. If the patch is not enough column confining pressure (f_l) necessary to ensure non-failure of the patch column can be expressed using the following equation:

$$f_l \geq \frac{A_b f_y}{\left[\frac{\pi D'}{2n} + 2(d_b + c)\right] l_s} \quad (1)$$

Where A_b is longitudinal bar area is patched, f_y the longitudinal rebar yield stress patched, D' the diameter of longitudinal reinforcement wrapping, n the number of longitudinal bars. The parameter d_b is diameter longitudinal bars patched, c the cover of longitudinal bars and l_s the length of the patch. Confining pressure required coating thickness steel, t, is calculated as follows:

$$t > \frac{f_l D}{400} \quad (2)$$

Where D is the diameter column.

4.2 Reinforced Concrete Jacketing

Concrete cover includes layers of, longitudinal bars and stirrups. Cover the concrete column and L profile increases bending strength and shear strength and increase ductility of the columns in this case is quite evident. Reinforced concrete cover in cases where the severity of damage is a high column or column does not have sufficient capacity to lateral forces is used. Fig. 2(b) shows the concrete jacketing considering L profile method for the column.

Concrete is also used to fill up the space between the reinforcements using the following equations:

$$N_{r,max} = 1.4\text{DL} + 1.7\text{LL} \quad (3)$$

Where $N_{r,max}$ maximum design load, DL and LL are dead load of column and the live load.
Where the cross sectional area of reinforcement bars, A_{st} calculated as following:

$$N_{r,max} = 0.8[0.85\phi_c f_c(A_g - A_{st}) + \phi_s f_y A_{st}] \quad (4)$$

Where f_c and A_g are the compressive strength of concrete and concrete sectional area.
Where the cross sectional area of L profile, A_s is given by

$$A_s = \frac{M_u}{\phi_s f_y d} \quad (5)$$

Where M_u is the ultimate design moment and d is the distance from extreme compression fiber to centroid of tension reinforcement. Finally, the process ends with the concrete jacketing considering L profile of structure. Section sizes of columns before and after corrosion are listed in Table 1.

Table 1: Column size before and after correction

	bonded steel plate	concrete jacketing
Before reform	40×40 cm^2	40×40 cm^2
After correction	D = 60 cm	60×60 cm^2

D = Diameter

The strengthened column is modeled and all values are controlled by CSA regulations. Then, the verified model is simulated for various concrete strengths and also different thicknesses of steel plates and steel L profiles. All the verifications for these developed models are implemented by assigning the minimum quantities of Ø16 for reaching the closest results. According to the output values, the P-M interaction diagrams are obtained for the whole models as well as for both normal and corroded conditions of the column. Table 2 presents the numbers of Ø16 (n Ø16) for two retrofitting methods in details.

5 Cost optimization

Regarding to the values obtained from P-M interaction diagrams, the maximum amounts of bending moments and related values of axial loads deduced.

Table 2: Numbers of Ø16 for reinforcements of retrofitting methods.

Retrofitting methods		Fc (MPa)			
		25	30	35	40
Thickness of steel plates (cm)	0.5	16	14	12	10
	1	14	13	12	11
	1.5	10	10	9	6
	2	10	7	4	4
L profiles (cm)	4 L10*10*0.8	24	22	14	8
	4 L10*10*1	20	18	12	6
	4 L10*10*1.2	18	16	12	6
	4 L12*12*0.8	18	16	12	6
	4 L12*12*1	16	14	10	4
	4 L12*12*1.2	16	12	10	4
	4 L14*14*0.8	10	10	10	4
	4 L14*14*1	10	10	8	4
	4 L14*14*1.2	8	8	8	4

However, as the cost of concrete and reinforcement may increase or decrease independently, the total cost is optimized for a particular amount of axial load and bending moment and also a certain percentage of reinforcement. The details are provided as follows:

$$C = C_c + C_r + C_{sl} + C_{sp} \quad (6)$$

Where Cc = Cost of 1 m3 concrete for various compressive strengths and the common practice in designing a column, is by considering the compressive strength of concrete as 25, 30, 35 and 40 MPa with cost of 30, 35, 40 and 45$ per m^3 respectively.

C_r = Cost of reinforcement and C_{sl} = Cost of steel L profile by considering 1$/kg for both of them.

C_{sp}= Cost of steel plate as 1$/kg.

Further, separate analyses are conducted for all combinations of Table 2 to select an optimized retrofitted column which can help to acquire the optimum cost as well as the interaction diagrams.

6 Analysis and Results

6.1 P–M interaction diagram

Fig. 3 for the cases of 25, 30 and 35 MPa compressive strength (Fc) of concrete columns shows the interaction diagrams for the results of externally-bonded steel plates respectively without considering the strength reduction (Ø) and environmental factors (CE) in these interaction diagrams.

The legend of each plot indicates various thicknesses of steel plates in range of 0.5 to 2 cm corresponding to the retrofitted column and also the initial and corroded situations of column.

Comparing the results before and after corrosion shows that the moment and compression axial load sustains 15, 20% reductions respectively. Scrutinizing the behavior of the column confirms that the plate's increasing thickness boosts the axial load capacities about 20% but the bending moments do not maintain considerable growth. On the other hand, the increase in plate thickness does guarantee the rise of M values. Also, there are similar trends for Fc of 30 and 35 MPa.

It can be mentioned here that in each of three Figs, the interaction diagram for t=2 cm of retrofitting steel plates has the most integral area under the curve (A) in the diagrams, so it can be concluded that, from the safety point of view, the P and M values related to the thickness are the optimal designs for all the diagrams. Finally, comparing each Fig, the amount of A for the diagram related to Fc equal to 25 MPa is the maximum value in all available situations, therefore its P, M, t and Fc amounts would be the most optimal designs.

Fig. 4 shows the interaction diagrams for the concrete jacketing considering L profile method using various numbers and thicknesses of steel L profiles for the Fc of 25 MPa. This method is similar to the previous one and displays the same trends in all 3 Figs, thus the increase of the number of L profiles as well as their thicknesses is reflected in the interaction results. Further evaluations confirm that the results of each Fig for t=1.2 cm of L profiles are most satisfying. However, where t=0.8, 1 and 1.2 cm of L profiles are 14, 12 and 10 respectively yielded similar results.

Overall, of all Figs, the results acquired from 12*14*14 are more satisfying than those of others since it has most integral area under the curve. Thus, the optimum status can be acquired by considering the cost of each parameter.

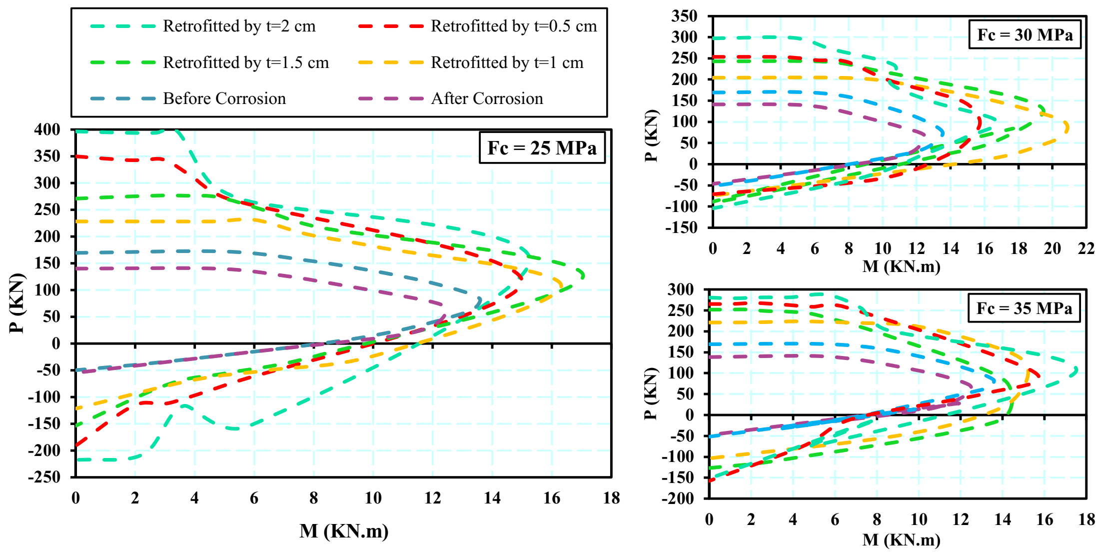

Figure 3: P-M interactions for externally bonding steel plates for different values of Fc.

In addition, surveying the whole process, the outputs of 14*14*1.2 L profiles offer the highest value for A among all diagrams.

Comparing both retrofitting methods for Fc of 25 MPa in the same conditions indicates that applying external steel plates shows about 40% increase in maximum loading capacity of the column comparing to use concrete jacketing with steel L profiles which can play a significant role in choosing retrofitting method especially when the costs are brought to attention too. Therefore, the optimization of costs is conducted for the following section.

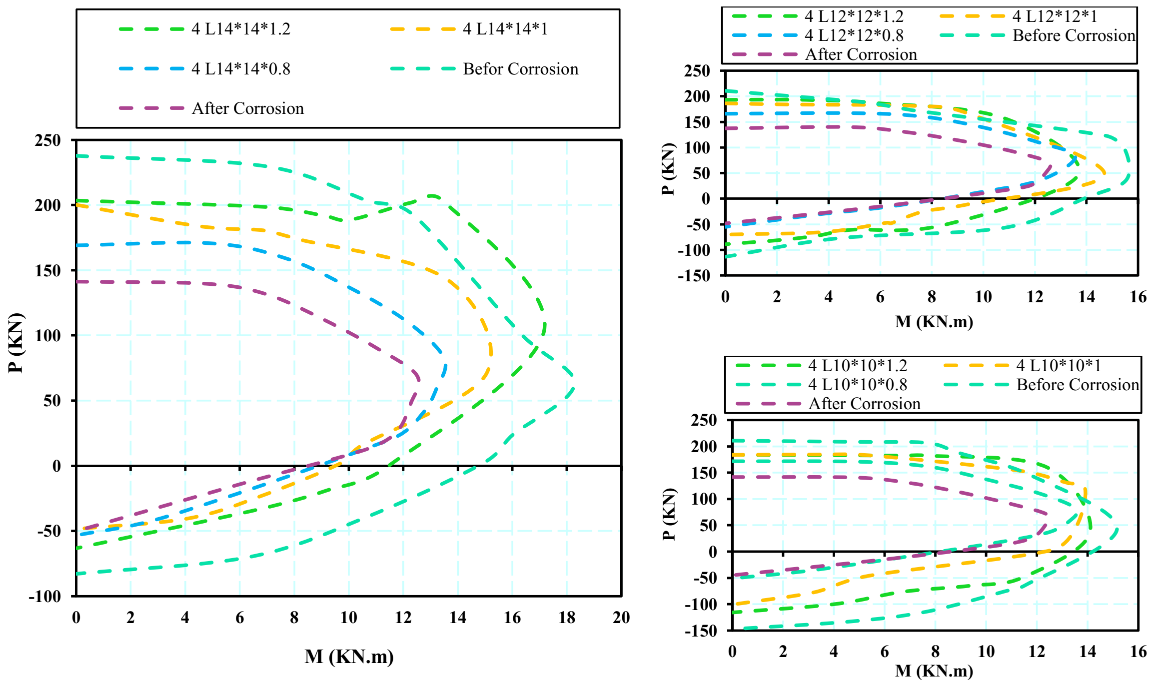

Figure 4: P-M interactions for concrete jacketing method for various numbers and thicknesses of steel L profiles with Fc of 25 MPa.

6.2 Selecting Retrofitting method using optimization

It is better to use optimization method to study the P-M diagrams and identify their best conditions. To do so, MATLAB was employed to optimize the loading capacity; safety issues, and, later, costs.

Fig. 5(a) shows the interaction diagrams for cost optimization of retrofitting the external steel plates. According to the results, increasing of Fc decreases the rebar numbers. Also, the most effective parameter in total cost is the steel plates due to their adjacency to each other. The intersection points display the optimal cost of design parameters which can be achieved for various concrete Fcs as well as plate thicknesses of. For example, for concrete Fc of 40 MPa, the intersection points are 7, 260 and 1.05 for rebar number Ø16, cost and plate thickness of respectively. Obviously, there is a %40 cost reduction in Fc 25. Besides, these Matlab interaction diagrams can significantly help to specify the optimal cost and design parameters.

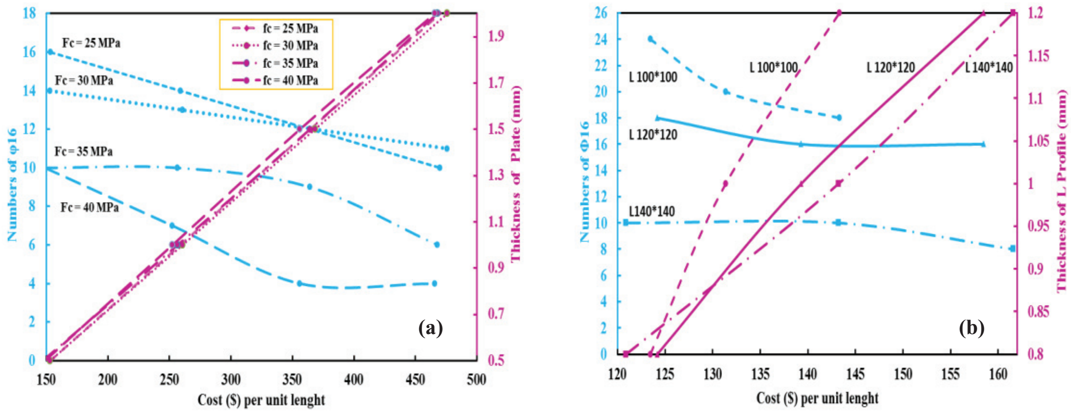

Figure 5: Comparing Rebar Ø16 and plate thickness in terms of the costs ($) per unit length for various (a) F_c and (b) L profiles.

Fig. 5(b) shows that the increasing number of steel L profiles typically decreases the numbers of rebar Ø 16 used for reinforcing. So, the change range in numbers of Ø16 for 100*100 L profile is broader than that of the other two. The interaction points of the diagram may be expressed as the optimal design circumstances for having the minimum amount of cost, proper numbers of Ø16 and thickness due to being in allowable values of regulation. For example, considering L 140*140, the optimal numbers of Ø16 for thickness and cost will be 10, 0.95 and 138 respectively. Furthermore, it can be also claimed that these optimization methods would be applicable for other ranges of F_c, thicknesses of L profiles, concrete jacketing, and interaction of whole parameters, each can have an important role in designing procedures. Optimization methods are mostly used to calculate optimal costs and methods, similar to what has previously been done. Here, to acquire better optimization, it seems necessary to consider the optimum cost along with the optimal amounts of P and M.

Fig. 6(a) depicts the interaction of P and M numbers of Ø16, steel plate thicknesses, and total cost of retrofitting. The results show that the number of Ø16 reduces for the constant M and while P rises, the plate thickness as well as total cost increase, too. It can be used, on the other hand, to specify the cost, thickness, and number of Ø16 for particular values of P-M interactions. Fig. 6(b) shows the relationship between the design parameters incorporating L profiles number of Ø16 for the reinforced concrete jacking (RCJ). This contour can be used to optimize any engineering design with different values of design parameters particularly P and M. So that for each specified parameters, the optimal cost can be identified also.

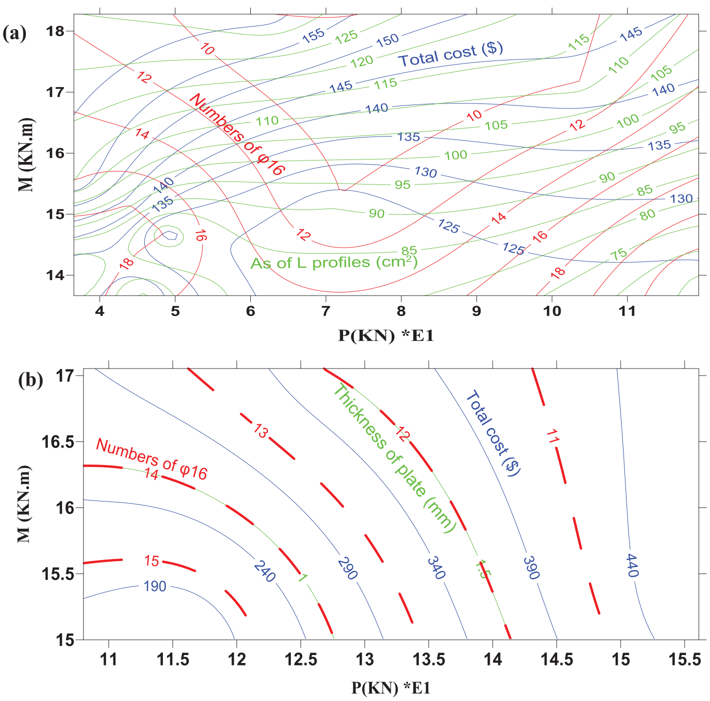

Figure 6: Range of design parameters retrofitting with (a) steel plates and (b) L profile numbers of Ø16.

7 Conclusion

Selecting an appropriate retrofitting method for concrete structures is significantly important especially from cost optimization point of view. Thus, the analysis, design, and implementation of the optimization method should provide maximum P and M along with safety since it leads to better performance under various Ps and Ms. The analysis can also help engineers to identify the effects of various materials on the P and M. In the case study of the salt factory, two types of retrofitting methods were applied to a %20 critically-corroded column. The results are as follows:

1. Considering 'merely' safety factors, applying externally-bonded steel plate yields about %40 growths in comparison to concrete jacketing retrofitting which means implementing steel plates are safer than using concrete jacketing retrofitting.
2. However, considering all parameters involved in design procedures for the constants P and M, the concrete jacketing retrofitting shows approximately %70 decrease in total cost which makes it more economical comparing to the other method.
3. Finally, these optimization methods are applicable to any types of retrofitting methods which simultaneously include both safety and minimum costs.

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