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OPTIMIZED SEISMIC RETROFIT OF STEEL-CONCRETE COMPOSITE FRAMES

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Abstract. *The present paper investigates the optimum way of reinforcing existing composite steel-concrete structures that violate the criteria suggested in Eurocode 4. The motivation to conduct the specific research is the need for existing structures to conform to new regulations without extensive operations.*

Composite steel-concrete systems are an attractive construction method, since they have been found to be cost-effective, especially for multi-storey buildings, and also successfully take advantage of the high stiffness of steel without its vulnerability to fire. These structural systems are not new and have been used since the beginning of the 20th century, so there is a number of existing structures which have been designed with previous versions of structural codes and have to conform to the modern regulations. It is obvious that each new set of design codes takes into account new dangers that might occur and updates the design methods already used. On the other hand, the economic considerations which have to be taken into account and the high market competition force the engineers to seek solutions that are at the same time easily and rapidly constructed, but also yield the required performance with the minimum cost.

The present work presents two retrofit methods for composite steel-concrete frames, which are evaluated in the context of structural optimization. The frames considered fail to satisfy the provisions of Eurocode 4 and are therefore retrofitted with the two aforementioned methods in a way minimizing the total cost of steel and concrete required for the retrofit. This way, the frames are upgraded with minimal cost.

1 INTRODUCTION

The present paper investigates the optimum way of reinforcing existing composite steel-concrete structures that violate the criteria suggested in Eurocode 4. The motivation to conduct the specific research is the need for existing structures to conform to new regulations without extensive operations.

Composite steel-concrete systems are an attractive construction method, since they have been found to be cost-effective, especially for multi-storey buildings, and also successfully take advantage of the high stiffness of steel without its vulnerability to fire. These structural systems are not new and have been used since the beginning of the 20th century, so there is a number of existing structures which have been designed with previous versions of structural codes and have to conform to the modern regulations. It is obvious that each new set of design codes takes into account new dangers that might occur and updates the design methods already used. On the other hand, the economic considerations which have to be taken into account and the high market competition force the engineers to seek solutions that are at the same time easily and rapidly constructed, but also yield the required performance with the minimum cost.

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2 RETROFIT METHODS

The retrofit philosophy used is the same for both methods presented in this work: the creation of an external layer of concrete with a metal cage that enhances the initial section's capacity and also confines the additional concrete. The difference between the two methods is in the type of reinforcement used. In the first method emphasis is given to steel, while the second method focuses on the use of concrete.

2.1 Method 1: Plates Method

This retrofit consists vertically of three plates per side; one rectangular and two of Γ-shape and horizontally of a number of rectangular plates that can be determined by the shear resistance criterion. The horizontal plates can be welded on the vertical ones or be added externally. The second option might seem easier to construct, but results in thicker concrete cover. Obviously, since there are only the cover concrete layer and a few patches between the plates, the concrete's contribution to the section's capacity might be ignored. However, in the present research, it has been taken into account.

The installation procedure is quite simple. The external smear is removed and steel plates are placed in touch with the existing concrete, as shown in Fig. 1. Depending on the construction method used, the whole cage might be in two parts, which are welded together on site, or independent horizontal and vertical plates that are welded one by one, as mentioned before (the horizontal ones at the outer side). Thus, a steel cage of the form shown in Fig. 2 is constructed. Then, the gaps between the plates and the desired concrete cover are filled with concrete.

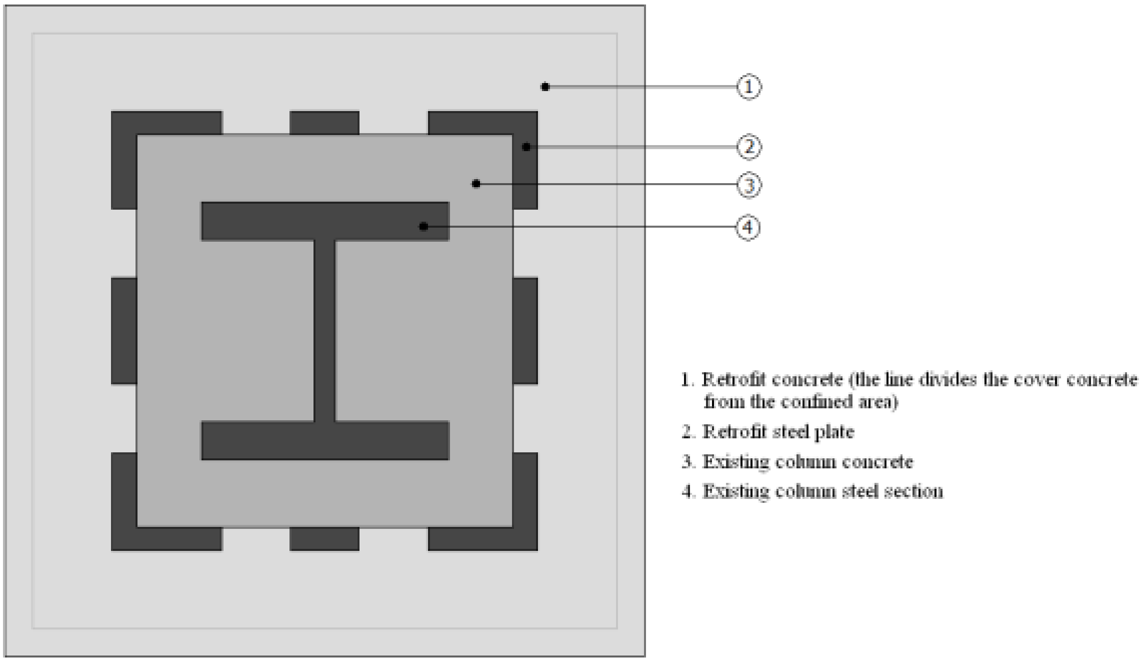

Figure 1: Cross-section of the retrofitted column (plates method).

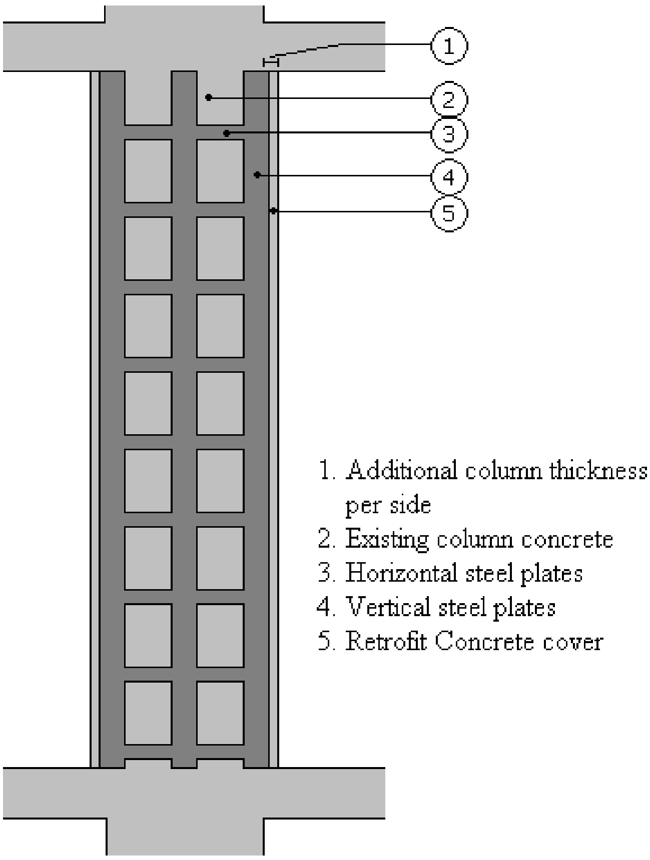

Figure 2: View of the cage on the column (plates method).

2.2 Method 2: Bars Method

In this method, the concrete is not only on the cover of the retrofit, but also in its core. The design of the new section is done with the typical philosophy of retrofitting a reinforced concrete column; there is longitudinal and transverse reinforcement surrounding the concrete, which contribute to the section's bending moment and shear capacity. The longitudinal reinforcement consists of 3 to 5 bars per side, depending on the dimensions of the existing column. The transverse reinforcement consists of rectangular stirrups that travel around the column. The location of the longitudinal bars is shown in Fig. 3, while the cage formed is illustrated in Fig. 4. The external smear has to be removed here too, in order to install the retrofit set-up. Contrary to the plates method, a rough surface of the existing concrete would increase the adhesion of it with the new concrete.

3 THE OPTIMIZATION PROBLEM

The objective function that has to be minimized is the total cost of retrofit that is calculated as:

$$P_{ref} = P_C \cdot V_C + P_S \cdot V_S \tag{1}$$

where P_{ref}: the total retrofit cost calculated in local currency
P_C: the total cost for the concrete in local currency per m^3
P_S: the total cost for the steel in local currency per m^3
V_C: the total volume of concrete (m^3)
V_S: the total volume of steel (m^3)

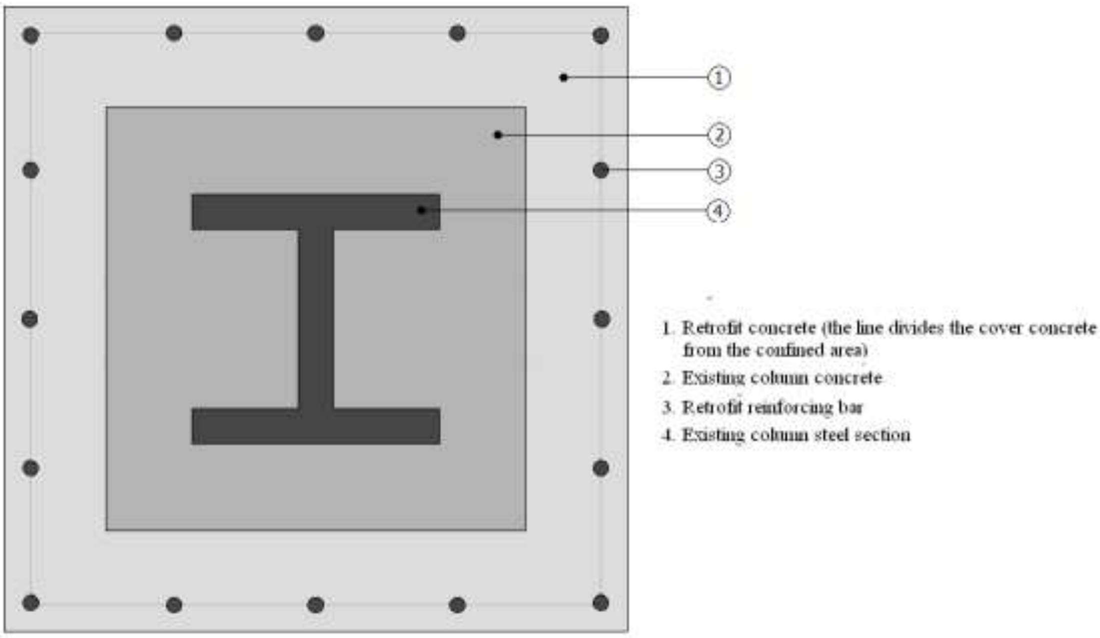

Figure 3: Cross-section of the retrofitted column (bars method).

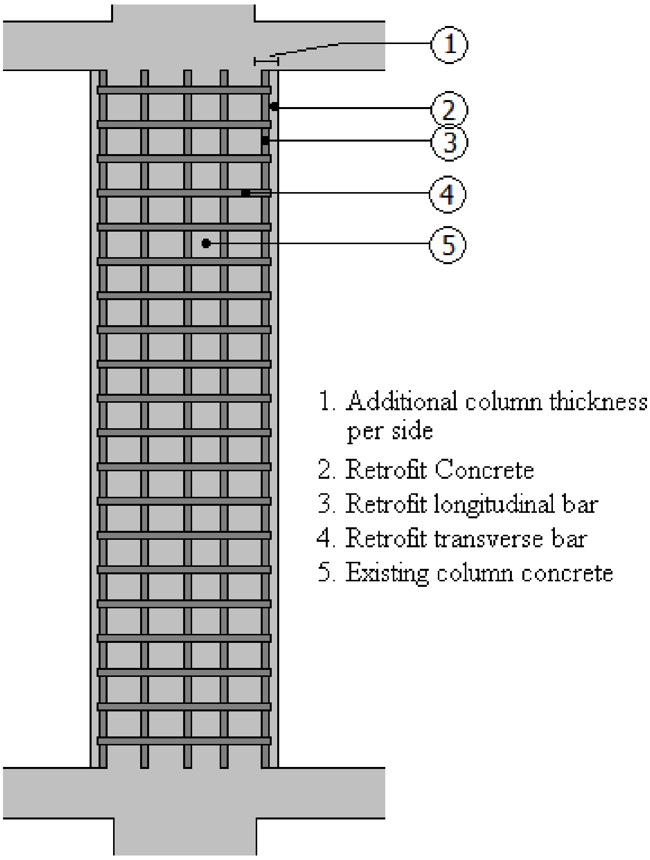

Figure 4: View of the cage on the column (bars method).

It is obvious that since the total volume of each material is its total area on the floor plan multiplied by the total height of the column (ground to top), it can be appropriately replaced in the abovementioned function. Also, the data used provide the retrofit cost in units of currency, so each time the price changes the whole problem would have to change. Therefore, the price ratio of concrete cost to steel cost was used instead. Applying these changes, the retrofit cost is finally calculated as:

$$P_{ref} = CR \cdot A_C + A_S \tag{2}$$

where P_{ref}: the total retrofit cost calculated in equal steel area (m^2)
CR: the cost ratio of the concrete cost to the steel cost ($CR = P_C/P_S$)
A_C: the total area of concrete on the storey (m^2)
A_S: the total area of steel on the storey (m^2)

The buildings' dimensions and the mechanical properties of the materials both on the existing section and the retrofit are not altered during the optimization procedure. All section dimensions including the beams, the columns and the retrofit are subject to change, depending on the problem solved (see next section). The data from which the optimizer chooses design variable values are provided in Table 1. The proportion dimension of each plate's height and breadth to the existing section's respective values is symbolized as β. Since there are three plates per side, the value of β cannot exceed the limit of $33{,}3\% \cdot \left(h + 2 \cdot t_{cg}\right)/h \cong 33{,}3\%$.

No.	HEB Section				IPE Section				Plates method		Bars Method	
	height	breadth	flange thick-ness	web thick-ness	height	breadth	flange thick-ness	web thick-ness	plate thick-ness	dimension propor-tion	total concrete thick-ness	bar di-ameter
	h (m)	b (m)	t_f (m)	t_w (m)	h (m)	b (m)	t_f (m)	t_w (m)	t_{cg} (m)	β	t_{ref} (m)	φ (m)
1	0.100	0.100	0.010	0.006	0.080	0.046	0.005	0.004	0.000	0%	0.000	0.000
2	0.120	0.120	0.011	0.007	0.100	0.055	0.006	0.004	0.005	5%	0.075	0.050
3	0.140	0.140	0.012	0.007	0.120	0.064	0.006	0.004	0.010	10%	0.100	0.012
4	0.160	0.160	0.013	0.008	0.140	0.073	0.007	0.005	0.010	20%	0.100	0.020
5	0.180	0.180	0.014	0.009	0.160	0.082	0.007	0.005	0.010	30%	0.100	0.025
6	0.200	0.200	0.015	0.009	0.180	0.091	0.008	0.005	0.015	10%	0.100	0.032
7	0.220	0.220	0.016	0.010	0.200	0.100	0.009	0.006	0.015	20%	0.150	0.012
8	0.240	0.240	0.017	0.010	0.220	0.110	0.009	0.006	0.015	30%	0.150	0.020
9	0.260	0.260	0.018	0.010	0.240	0.120	0.010	0.006	0.020	10%	0.150	0.025
10	0.280	0.280	0.018	0.011	0.270	0.135	0.010	0.007	0.020	20%	0.150	0.032
11	0.300	0.300	0.019	0.011	0.300	0.150	0.011	0.007	0.020	30%	0.200	0.012
12	0.320	0.300	0.021	0.012	0.330	0.160	0.012	0.008	0.025	10%	0.200	0.020
13	0.340	0.300	0.022	0.012	0.360	0.170	0.013	0.008	0.025	20%	0.200	0.025
14	0.360	0.300	0.023	0.013	0.400	0.180	0.014	0.009	0.025	30%	0.200	0.032
15	0.400	0.300	0.024	0.014	0.450	0.190	0.015	0.009	0.030	10%	0.250	0.012
16	0.450	0.300	0.026	0.014	0.500	0.200	0.016	0.010	0.030	20%	0.250	0.020
17	0.500	0.300	0.028	0.015	0.550	0.210	0.017	0.011	0.030	30%	0.250	0.025
18	0.550	0.300	0.029	0.015	0.600	0.220	0.019	0.012	0.040	30%	0.250	0.032
19	0.600	0.300	0.030	0.016	-	-	-	-	-	-	-	-
20	0.650	0.300	0.031	0.016	-	-	-	-	-	-	-	-
21	0.700	0.300	0.032	0.017	-	-	-	-	-	-	-	-
22	0.800	0.300	0.033	0.018	-	-	-	-	-	-	-	-
23	0.900	0.300	0.035	0.019	-	-	-	-	-	-	-	-
24	1.000	0.300	0.036	0.019	-	-	-	-	-	-	-	-

Table 1: Database used to define the section dimensions.

The constraints of the optimization problem include the member checks defined in Eurocode 4, which are evaluated with the help of linear analyses for each candidate optimum retrofit design. Additionally, performance constraints are imposed, which are evaluated using pushover analysis results.

The discrete optimization algorithm implemented is based on the evolution strategies method. The analysis platform employed for linear and pushover analyses is the software system Opensees.

4 NUMERICAL RESULTS

In order to determine the effect of the building's height to the optimum retrofit design, two buildings were simulated; a two-storey and a four-storey, which have the same floor plan (Figs. 5-6). The beams' span is 5.50m in both directions and the columns' height is 3.50m.

Because of the problem's complexity and the significant demand for computational effort, translated into several computer hours for each optimization, four sets of runs were conducted, where the succeeding one would benefit from the results of the previous one and also conclusions would be extracted at each stage. It is noticeable that each step requires much more analyses than the previous one.

Four groups od design variables are defined for both buildings. Group 1 includes all design variables associated with corner columns. Groups 2 and 3 refer to all side columns in *x*-direction and *y*-direction, respectively. Finally, Group 4 involves all internal columns of the 3D frame.

The aim of the first set was to determine the optimum design for both buildings, in order not to require retrofit (Eurocode 4 provisions satisfied). So, during this set, the retrofit parameters were set to zero and the initial sections of the columns and beams were chosen from databases of standard I-sections: HEB sections were used for the columns and IPE sections for the beams. The algorithm was allowed to choose the steel section for the columns, but the concrete cover layer was the same for all columns (5cm per side). Previous tests had shown that the contribution of the cover concrete is minimal, so this parameter could be ignored for the purposes of this research. The optimum design obtained for the two-storey building was HE400B for all column sections and IPE450 for the beams (Table 2). The respective results for the four-storey building are given in Table 3.

The second set of tests was similar to the first one. Its purpose was to examine whether the Eurocode 4 criteria were those that determined the optimum design or it is also influenced by the building's performance constraints. So, in this scenario, the Eurocode 4 criteria were deactivated and the algorithm was allowed to determine the optimum design choosing from a variety of initial sections including the combinations that had been rejected in the previous set, because the Eurocode 4 criteria were not fulfilled. According to the results of these runs, even smaller sections seem to be adequate for the beams, some of which would not even be able to bear the dead loads of the slabs. On the other hand, the selection of column sections was mostly determined by the structure's performance, especially for the four-storey building. The designs provided by the algorithm are presented in Table 4.

One can see in Table 4 that the use of a large section in one group and small sections for the other three seems to be much more efficient than the use of the same section in all four groups of columns. It is probably because such a selection increases the total stiffness without respective increase of the cost. However, this is only a mathematical optimum, since in both buildings the three out of four sections do not pass the Eurocode 4 criteria when tested independently.

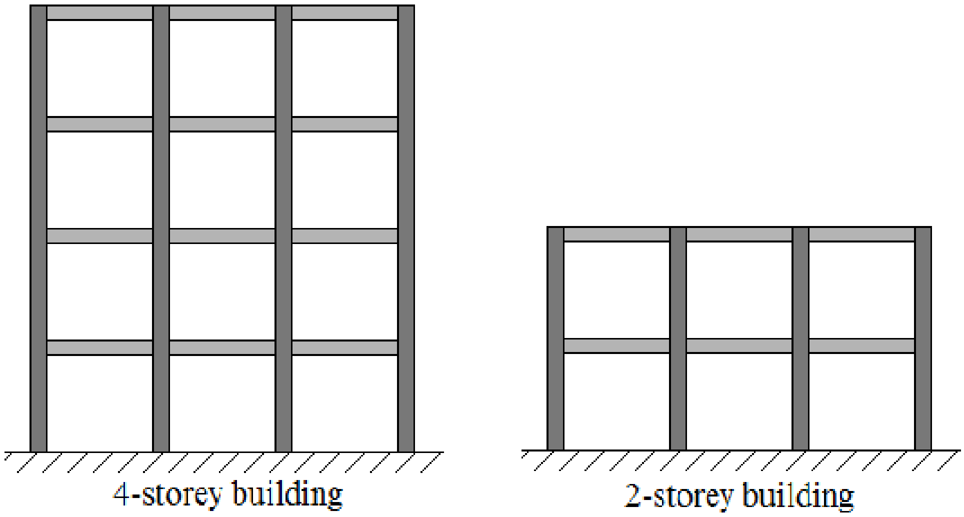

Figure 5: View of the two buildings.

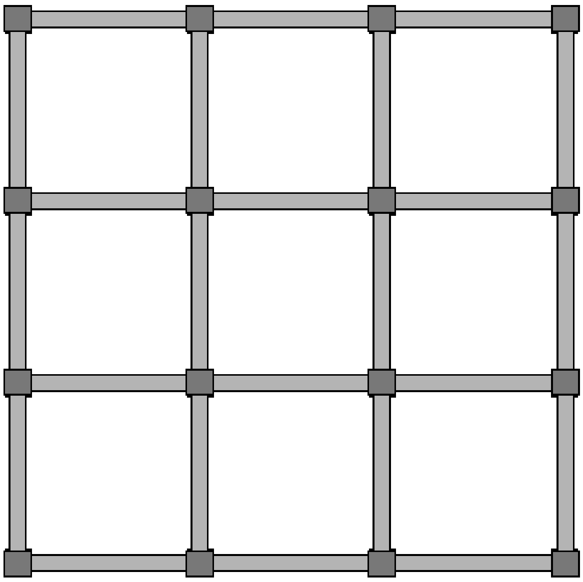

Figure 6: Floor plan for both buildings.

Section Group	Group 1	Group 2	Group 3	Group 4	Beams
Steel Section Type	HE400B	HE400B	HE400B	HE400B	IPE450

Table 2: Characteristics of the optimum design for the two-storey building.

Section Group	Group 1	Group 2	Group 3	Group 4	Beams
Steel Section Type	HE600B	HE400B	HE450B	HE800B	IPE450

Table 3: Characteristics of the optimum design for the four-storey building.

Section Group	Group 1	Group 2	Group 3	Group 4	Beams
Steel Section Type	HE700B	HE180B	HE180B	HE180B	IPE200

Table 4: Optimum design for the two-storey building without Eurocode 4 constraints.

Section Group	Group 1	Group 2	Group 3	Group 4	Beams
Steel Section Type	HE180B	HE200B	HE240B	HE1000B	IPE200

Table 5: Optimum design for the four-storey building without Eurocode 4 constraints.

Comparison of the storeys' stiffness shows that they are of similar philosophy with the ones provided for the two-storey building, so one could conclude that the Eurocode 4 criteria do not determine the optimum design, but lead the algorithm to a more appropriate result.

The third set of tests aimed to determine the effect of the cost ratio (concrete price to steel price), since it was used in order to convert the concrete area to corresponding steel area. Two values of cost ratio were used: 40% and 10%. The initial sections were all the same for the four groups, but the retrofit dimensions could be different for each group. Only designs rejected at the first series of tests were used, including one per building that should not require retrofit as a control section. The results obtained are given in Tables 6-8.

Comparing the optimum design independently for each method of retrofit, it is evident that the cost ratio severely influences the most cost-effective solution, but not dramatically, since the total storey stiffness is almost the same in both cases. As was expected, the retrofit solutions with more concrete (bars method) are preferable when the cost ratio is low. On the other hand, higher cost ratios make the design with plates a more attractive solution. It should be noticed that, for initial steel sections HE260B, HE280B and HE300B, the optimum retrofit method is different for the two cost ratios considered.

Steel Section	Plates		Bars	
	Combination	**Cost**	**Combination**	**Cost**
HE180B	**1-1-18-18**	0.1151	**1-1-1-3**	0.0619
HE200B	**1-1-12-1**	0.0983	**1-1-1-3**	0.0651
HE220B	**1-1-3-18**	0.0873	**1-1-1-3**	0.0683
HE240B	**1-1-18-1**	0.0693	**1-1-1-2**	0.0686
HE260B	**1-17-1-1**	0.0577	**1-1-1-2**	0.0710
HE280B	**1-1-16-1**	0.0525	**1-1-1-2**	0.0734
HE300B	**1-1-8-1**	0.0406	**1-1-1-2**	0.0758
HE320B	**1-1-1-5**	0.0335	**1-1-1-2**	0.0770
HE340B	**1-1-1-3**	0.0283	**1-1-1-2**	0.0782
HE360B	**1-1-1-2**	0.0228	**1-1-1-2**	0.0794
HE400B	**1-1-1-1**	0.0000	**1-1-1-1**	0.0000

Table 6: Optimum retrofit for the two-storey building (cost ratio 0.4).

Steel Section	Plates		Bars	
	Combination	Cost	Combination	Cost
HE180B	1-2-18-18	0,0834	1-1-1-3	0,0168
HE200B	1-3-18-16	0,0742	1-1-1-3	0,0176
HE220B	1-1-5-18	0,0607	1-1-1-3	0,0184
HE240B	1-1-1-18	0,0488	1-1-1-3	0,0192
HE260B	1-1-1-17	0,0409	1-1-1-3	0,0200
HE280B	1-1-1-16	0,0310	1-1-1-3	0,0208
HE300B	1-1-3-6	0,0228	1-1-1-3	0,0216
HE320B	1-1-1-9	0,0156	1-1-1-3	0,0220
HE340B	1-1-1-3	0,0105	1-1-1-3	0,0224
HE360B	1-1-1-2	0,0066	1-1-1-3	0,0228
HE400B	1-1-1-1	0,0000	1-1-1-1	0,0000

Table 7: Optimum retrofit for the two-storey building (cost ratio 0.1).

Initial Column Section	Cost Ratio = 0,4		Cost Ratio = 0,1		Optimum for Cost Ratio 0.4	Optimum for Cost Ratio 0.1
	Retrofit with plates	Retrofit with bars	Retrofit with plates	Retrofit with bars		
HE180B	0.1151	0.0619	0.0834	0.0168	bars	bars
HE200B	0.0983	0.0651	0.0742	0.0176	bars	bars
HE220B	0.0873	0.0683	0.0607	0.0184	bars	bars
HE240B	0.0693	0.0686	0.0488	0.0192	bars	bars
HE260B	0.0577	0.0710	0.0409	0.0200	plates	bars
HE280B	0.0525	0.0734	0.0310	0.0208	plates	bars
HE300B	0.0406	0.0758	0.0228	0.0216	plates	bars
HE320B	0.0335	0.0770	0.0156	0.0220	plates	plates
HE340B	0.0283	0.0782	0.0105	0.0224	plates	plates
HE360B	0.0228	0.0794	0.0066	0.0228	plates	plates
HE400B	0.0000	0.0000	0.0000	0.0000	plates	plates

Table 8: Comparison of the optimum retrofit method.

The final and most demanding set of optimization runs intended to determine the exact value of the cost ratio, for which both retrofit methods would have the same cost, calculated in equal steel area. Since this is a continuous parameter that does not take specific (discrete) values, as applies to section dimensions, the number of optimization runs needed would be infinite. In order to reduce the computational cost, there were targeted optimization runs using various values of the cost ratio until a converged results was obtained. The results are presented in Figs. 7-9.

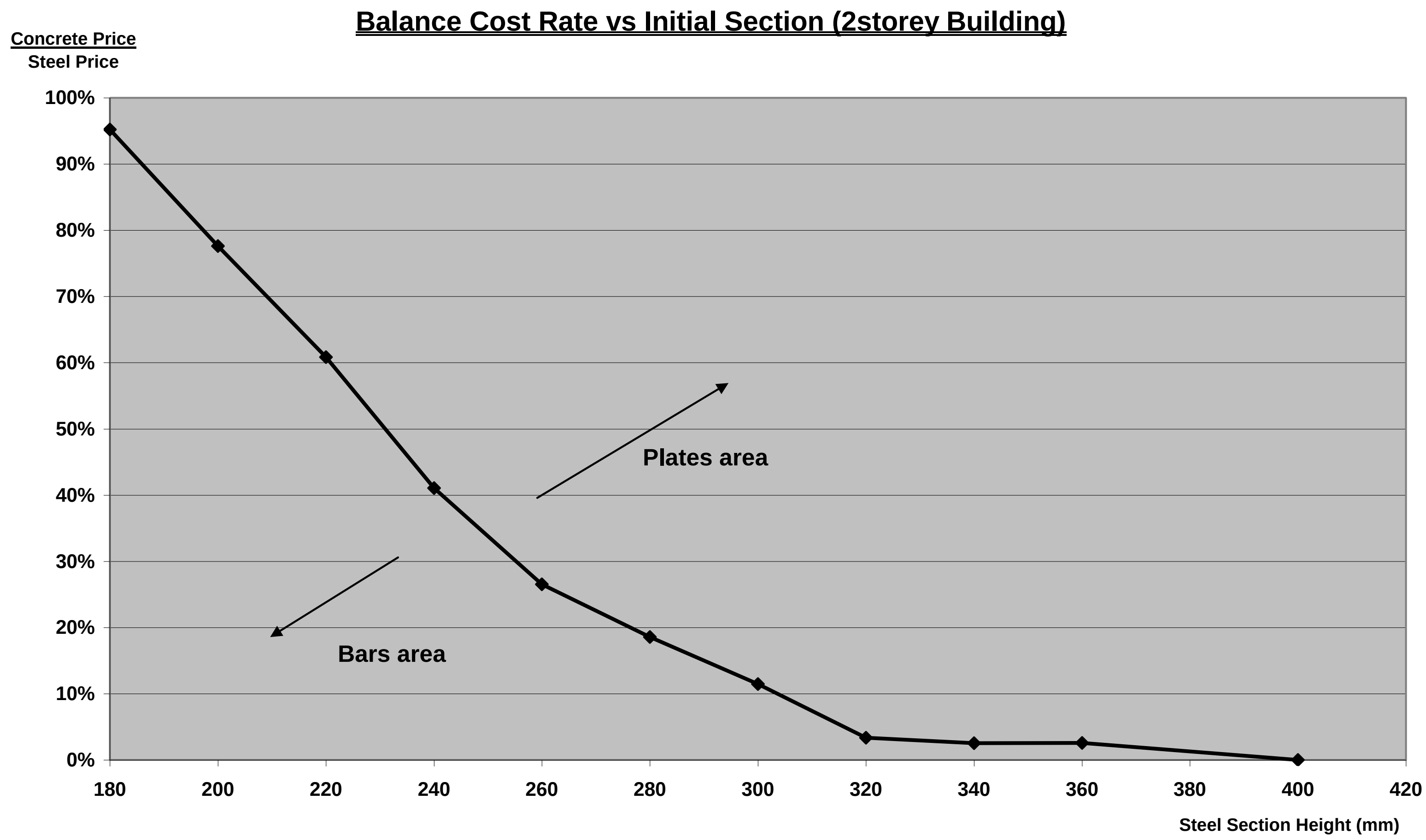

Figure 7: Balance cost ratio for the retrofitted sections for the two-storey building.

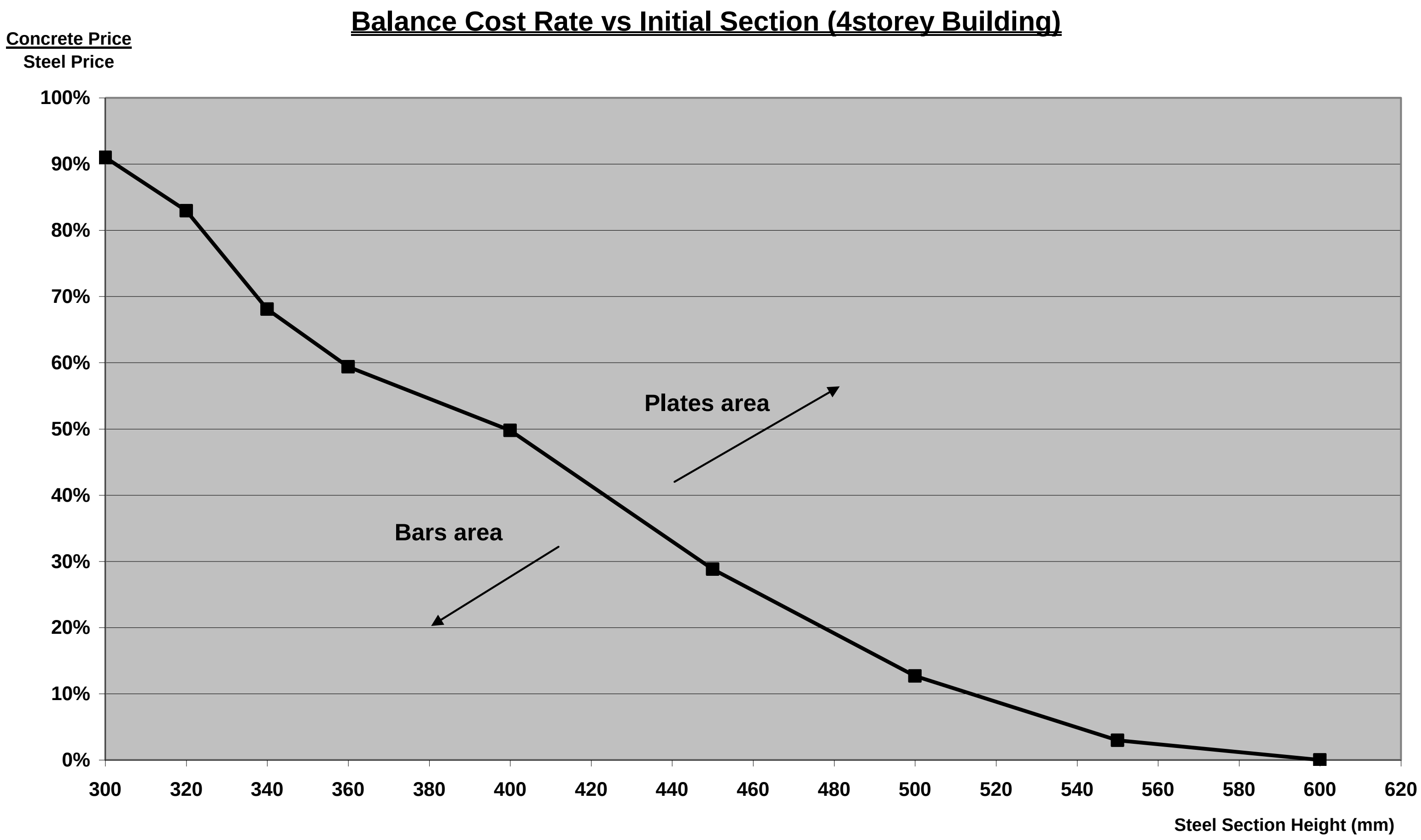

Figure 8: Balance cost ratio for the retrofitted sections for the four-storey building.

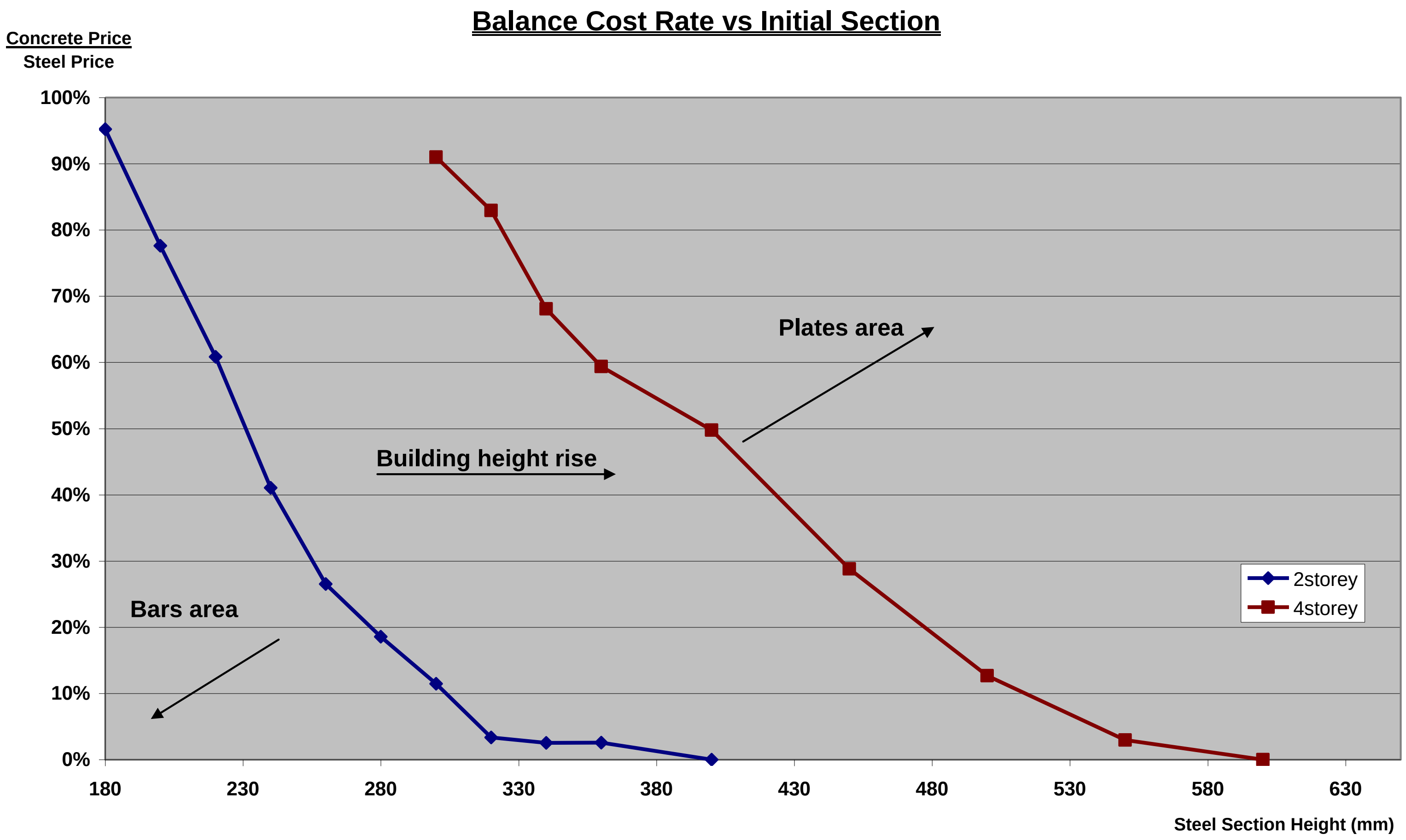

Figure 9: General diagram of the balance cost ratio for the retrofitted sections for both buildings.

5 CONCLUSIONS

- Both methods of retrofit improve the structure's response.
- The variable that has the most significant effect on the selection of the optimum retrofit method seems to be the ratio of the concrete price to steel price.
- Low cost ratios make the bars method a more attractive choice, but this is reversed for higher ratio values.
- Another important factor is the initial steel section, since for sections that are not far below the optimum design, the plates method is dominant even for low cost ratios.
- Finally, the building height seems to move the balance cost ratio versus initial steel section height diagram to the right, increasing this way the bars method area. Note that the comparison is made within the feasible solutions region of the design space for each building.

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