PARAMETRICAL ANALYSIS OF WAREHOUSE PRESTRESSED PRECAST CONCRETE BEAMS

Lisiane Pereira Prado

lisianeprado@usp.br

Rafaella Moreira Lima Gondim Resende

rresende@usp.br

Carol Ferreira Rezende Santos

carolrezende@usp.br

Yagho de Souza Simões

yaghosimoes@usp.br

Escola de Engenharia de São Carlos - EESC/ Universidade de São Paulo

Av. Trabalhador são-carlense, 400, Parque Arnold Schimidt. CEP 13566-590 - São Carlos - SP.

Rafaela Derêncio Alvarenga

rafaela@usicon.com.br

Abstract. *Concrete is the most used material in the production of elements in civil construction (columns, beams and slabs). The development of concrete technology resulted in an increase in its mechanical properties, such as compressive strength and modulus of elasticity. This improvement, especially in compressive strength, culminated in slender elements, allowing greater versatility for the architectural projects and the design of more daring structures. Therefore, this work aims to analyze the use of pre stressed precast concrete beams in the design of warehouse with a 43000mm span, verifying the most economical solutions of cross-section variation, considering different heights of the beam (140cm, 150cm, 160cm and 170cm) and concrete compressive strengths (50MPa, 60MPa, 70MPa and 80MPa). The study will be done through an excel spreadsheet developed for the calculation of the proposed beam, considering ABNT NBR 6118:2014 and ABNT NBR 9062:2017. This research showed that the cost of concrete with higher compressive strength is prohibitive in the studied region (São Paulo – Brazil). The structural solution that resulted in the best budget is the use of I-beam with dimensions 70x12x21x170 and concrete compressive strength of 50MPa.*

Keywords: *Precast concrete beam, High strength concrete, Cost analysis*

INTRODUCTION

Concrete is the most commonly used material in construction industry due to its relative low cost, good resistance to water, ready availability and ability to adapt to different shapes. This ability favors the use of concrete as architectural element as well as part of the structure.

Regarding this, precast concrete offers even more architectural freedom than conventional concrete. El Debs (2000) defines precasting as a construction process where part of the structure (or the whole structure) is casted out of its definitive place. While conventional concrete beams have, mainly, rectangular cross sections, precast concrete allows the use of different shapes. The preference for rectangular shaped beams for cast-in-situ concrete is related to the ease to assemble its formwork, to place the reinforcements and to vibrate the element provided by this shape. However, the rectangular shaped cross section is not so effective for flexural elements since it has the same quantity of material throughout the section even in areas of low stress (around the neutral line). Therefore, this part of material that is not subjected stress could be removed in order to decrease the weight of the beam. The adoption of more optimized cross sections creates more advantages for precast concrete beams: less consumption of material decreases the structural cost and the smaller weight means less force applied on the beam. Hence precast concrete beams capability of covering longer spans with the same cross sectional height.

Other advantages of precast concrete are the economy of time during construction, the higher quality control due to the more industrialized process of casting and the reduction of costs in formwork and work force. The main disadvantages of this structural system are the higher cost of structural elements and the need of more specialized workers.

Given that precast concrete beams are mostly used in structures that have long spans (i.e., bridges, warehouses), prestress is often applied to improve their structural behavior. This procedure also favors architectural freedom, since it allows a reduction in cross sectional height and the design of lighter structures.

Debernardi and Taliano (2010) performed a parametric analysis to study the define limits to the span-to-height ratio of prestressed concrete beams and slabs. This analysis considered the design of a beam in the ultimate limit state (ULS) and the verification of its deflection in compliance with the Eurocode 2 and the Model Code 1990. The authors varied span, height, concrete strength, applied load and structural supports of the prestressed beams. The conclusions were summarized in Table 1. The total deflection is obtained under the quasi-permanent load combination. The active deflection is the one after construction that could damage elements close to the beams or slabs.

The Turner-Fairbank Highway Research Center (2006) evaluated the evolution of cost in bridge girders with the use of high-strength concrete for different cross sections. The analysis were performed with the computer program BRIDGE. The authors noticed that the use of high-strength concrete in bridge decks did not alter the necessary height of the elements. Therefore, it was concluded that this variation did not reduce material consumption. The authors also stated that the higher concrete strength allowed an increase in the maximum spans of the beams. Thus, although there is no cost savings due to reduction in material consumption, it is possible to reduce the structural cost adopting longer spans. The authors also concluded that the use of concretes with higher strength will result in a smaller live load deflection.

Table 1. Allowable span-to-height limits

	Simply supported beams				**Partially prestressed**			
	Fully prestressed		Partially prestressed		Simply supported		Fixed ends	
Q_k/G_k	Total	Active	Total	Active	Total	Active	Total	Active
0.25	32	23						
0.50	38	29	28	23	34	28	46	41
0.75	41	33						

Source: Debernardi and Taliano (2010)

This work aims to study different structural designs the beams of a warehouse with a 43m span. The structural system adopted is prestressed precast concrete. The solutions vary in cross sectional height, amount of prestress and characteristic compressive strength of concrete (f_{ck}). After the design, a cost analysis was performed.

2 METHODOLOGY

In order to perform this analysis, an excel spreadsheet was elaborated to automate the design of the beams. Given the geometrical characteristics of the cross section, the quantity of pre-stressed strand wires and the live and dead load applied on the beam, the spreadsheet calculates the longitudinal and transverse reinforcements as well as spalling reinforcements. The spreadsheet also verifies the deflection of the beam.

A simplified sketch of cross sections analyzed in this work is shown in Figure 1. The dimensions adopted for each of the sixteen beams are outlined in Table 2. The cross sectional parameters varied in this study were width of the flange (B_f), width of the web (B_w), height of the flange (h_f) and height (h). Each of the beams was designed using concretes with compression strength of 50MPa, 60MPa, 70MPa and 80MPa. The design was performed according to ABNT NBR 6118: 2014 and ABNT NBR 9062:2017.

The beams were designed to cover a span of 43000mm. The warehouse have 10 beams and the distance between them is 12500mm. The top view of the warehouse is shown in Figure 2. It was assumed that the tiles apply a pressure of 0,14kN/m² and that the water and electrical installations correspond to a pressure of 0,2kN/m². The live load was assumed 0,3kN/m². The wind load was disregarded. It was assumed that the mentioned pressures were applied to the beam through 10 small concrete columns evenly spaced throughout the beam. Each small column was assumed to have a weight of 160kg.

After designing the beams, the quantity of concrete, steel reinforcement and pre stressed strands necessary for each type of beam was computed. Then, based on these three parameters, the Caixa Econômica Federal (2017) database was used. The data was obtained for the city of São Paulo in July of 2017. The unit cost adopted for each component is shown in Table 3.

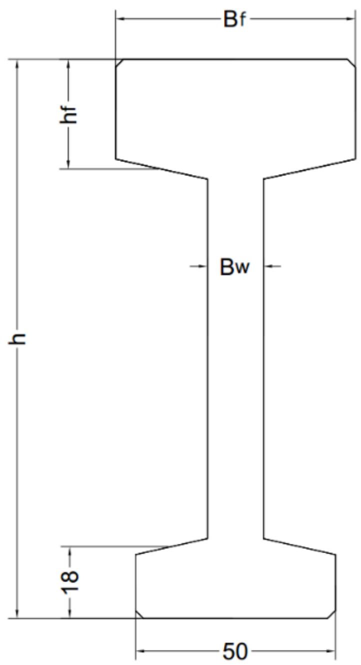


Figure 1. Simplified sketch of the cross section of the beam (units in cm)

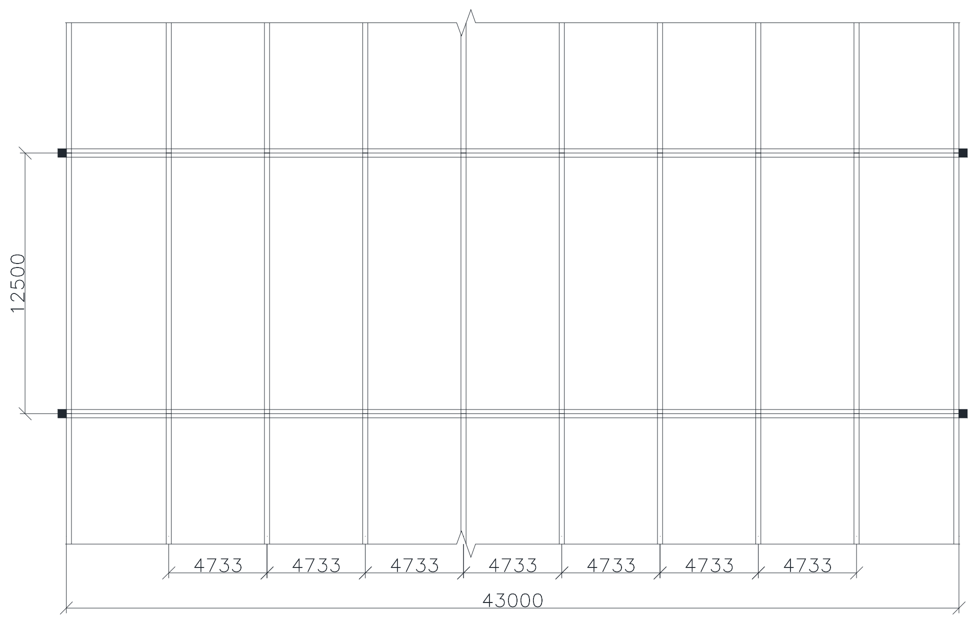


Figure 2. Top view of the warehouse (units in mm)

Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

Table 2. Dimensions adopted for each type of beam

Viga	**B_f (cm)**	**B_w (cm)**	**h_f (cm)**	**h (cm)**	**S (cm²)**	**y (cm)**	**I (cm4)**
I60x14x38	60	14	38	140	4325.00	81.30	9767088.07
I60x14x28	60	14	28	140	3865.00	78.18	9408839.67
I70x12x21	70	12	21	140	3642.25	77.49	9580910.03
I70x12x26	70	12	26	140	3932.25	80.37	9991144.12
I60x14x38	60	14	38	150	4465.00	87.15	11728423.80
I60x14x28	60	14	28	150	4005.00	83.66	11251176.62
I70x12x21	70	12	21	150	3762.25	82.87	11401580.94
I70x12x26	70	12	26	150	4052.25	85.99	11915573.47
I60x14x38	60	14	38	160	4605.00	92.95	13906923.26
I60x14x28	60	14	28	160	4145.00	89.11	13292010.69
I70x12x21	70	12	21	160	3882.25	88.23	13409344.63
I70x12x26	70	12	26	160	4172.25	91.58	14039626.88
I60x14x38	60	14	38	170	4745.00	98.70	16310125.15
I60x14x28	60	14	28	170	4285.00	94.54	15538513.70
I70x12x21	70	12	21	170	4002.25	93.56	15610292.84
I70x12x26	70	12	26	170	4292.25	97.14	16369554.98

Table 3. Unit cost of structural components

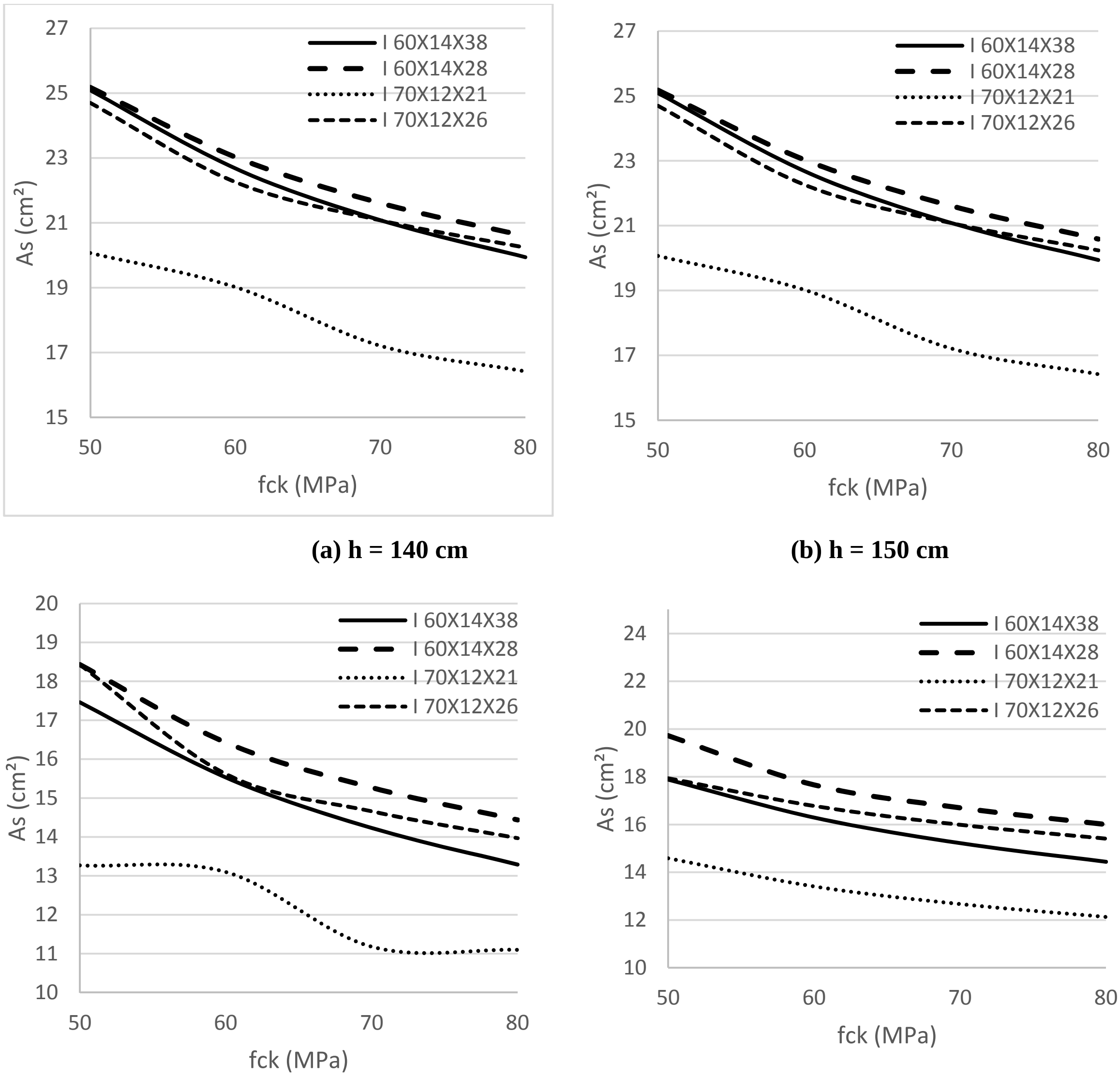
Material	Unit Cost
Concrete (compression strength 50MPa)	R$ 411,43 (m^3)
Concrete (compression strength 60MPa)	R$ 528,32 (m^3)
Concrete (compression strength 70MPa)	R$ 628,84 (m^3)
Concrete (compression strength 80MPa)	R$ 729,36 (m^3)
Steel CA-50	R$ 3,79 (kg)
Pre Stressed Strand CP-150	R$ 5,95 (kg)

3 RESULTS

Figure 3 shows the area of steel needed as a function of the concrete compressive strength to each analyzed beam height. The amount of pre stressed strands was determined in the ultimate limit state and, therefore, is not constant for each height.

The beam of cross section I 70x12x21 presented the smaller area of steel needed of all the studied beams. The advantage of this beam over the beams with 60cm flange width is its greater area of compressed concrete. On the other hand, although the I 70x12x26 beam has a larger compressed concrete area, this cross section lead to an inferior structural behavior. This happens because both beams are functioning as rectangular cross sections, instead of working as t-sections. Therefore, the greater flange height did not have positive influence over the area of steel and added to the self-weight load of the beam. The other analyzed cross sections showed similar behaviors for all heights and strengths considered.

For concrete compressive strengths varying in the 50MPa to 70MPa range, when the height of the beam was increased in 10cm, the area of steel was reduced in approximately 30%. This behavior was not observed when the concrete compressive strength was 80MPa. In this strength level, the height increase did not cause considerable decrease in area of steel because this value was already close to the normative minimum.



(a) h = 140 cm **(b) h = 150 cm**

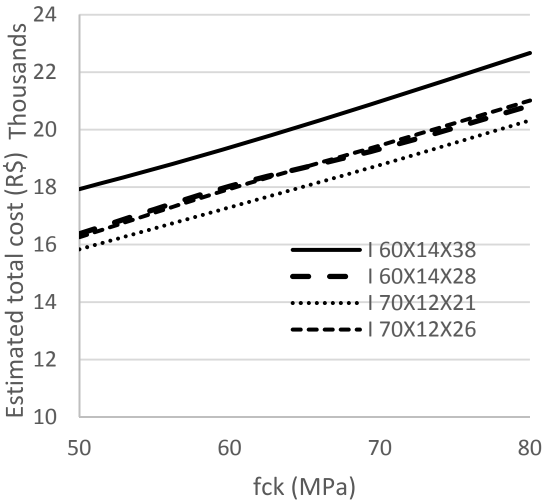
(c) h = 160 cm **(d) h = 170 cm**

Figure 3. Area of steel (cm²) as a function of concrete compressive strength (MPa)

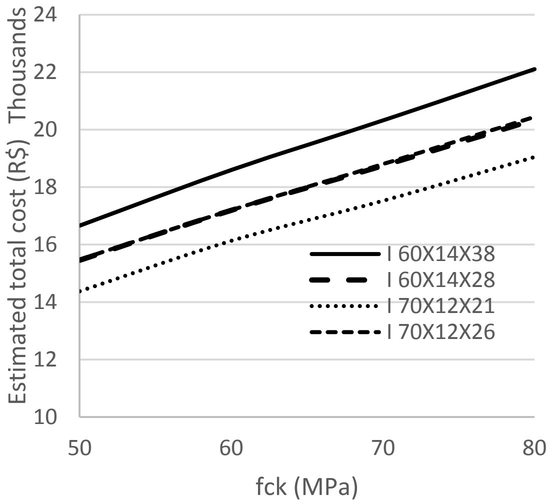
As shown in Figure 4,the I 70x12x21 beam had the lowest estimated total cost. This value reflects the better structural performance of this beam, that demanded the smallest area of steel.

The I 60x14x28 and I 70x12x26 cross sections showed roughly the same estimatedtotal cost once their geometrical characteristics (area and moment of inertia) are similar. Thus, the amount of steel needed for both beams is approximately equal.

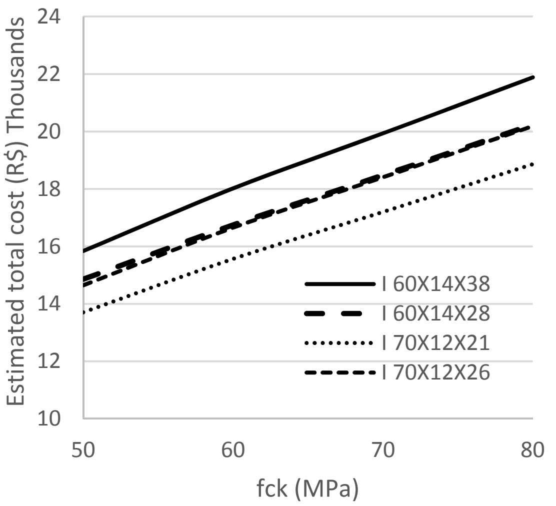
The I 60x14x38 beam had a higher cost due to its larger cross sectional concrete area. Though its greater concrete area, this beam needed more pre stressed strands and steel than the others, indicating that the concrete is not well distributed throughout the cross section. As an example, the flange height could be reduced since the girder works as a rectangular beam.



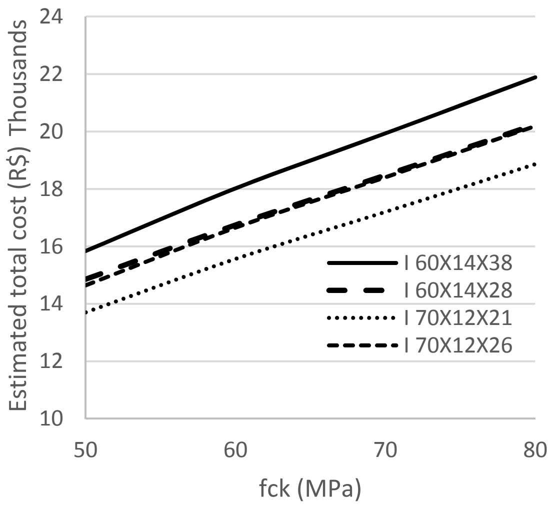
(a) h = 140 cm



(b) h = 150 cm



(c) h = 160 cm



(d) h = 170 cm

Figure 4. Estimated total cost as a function of concrete compressive strength (MPa)

The results show that the use of concrete with higher compressive strengths is not cost effective. Although the higher strength of the concrete reduces the steel needed for the beam, its high price in the studied region (São Paulo – Brazil) results in a prohibitive budget. Thus, the use of concrete with a compressive strength of 50MPa had the lowest cost.

Overall, the height of 160cm showed the best budget results, especially for concretes with compressive strength of 70MPa and 80MPa. For some beams with concrete compressive strength of 50MPa and 60MPa, the cross sectional height of 170cm showed the lowest cost. Due to the relatively low compressive strength, these beams needed a larger amount of steel and the increase in height reduced this quantity as well as the cost. However, with higher compressive strengths, the quantity of steel is already close to the normative minimum and, therefore, the increase in height from 160cm to 170cm did not generate a significant reduction in area of steel.

The data used to create the graphs in Figures 3 and 4 is shown in tables 4 through 7.

Table 4. Estimative of materials and cost (h=140cm)

Adopted cross section	f_{ck}- 28 days (MPa)	Quantity of pre stressed wires (Ø 12,7 mm)	Area of steel (As) (cm²)	Cross sectional area (m²)	Total cost (concrete + steel) (R$)
I 60X14x38x140	50	28	36,93	0,4325	17928,02287
I 60X14x38x140	60	28	31,24		19373,9547
I 60X14x38x140	70	28	29,21		20983,67455
I 60X14x38x140	80	28	27,77		22668,87397
I 60X14x28x140	50	26	34,3	0,3865	16381,18712
I 60X14x28x140	60	26	32,05		18035,99471
I 60X14x28x140	70	26	29,11		19330,46839
I 60X14x28x140	80	26	27,84		20838,58759
I 70X12x21x140	50	26	29,82	0,3882	15838,12976
I 70X12x21x140	60	26	25,99		17299,35032
I 70X12x21x140	70	26	24,4		18773,87946
I 70X12x21x140	80	26	23,43		20327,72611
I 70X12x26x140	50	22	36,22	0,3932	15952,21349
I 70X12x26x140	60	22	33,38		17565,21753
I 70X12x26x140	70	22	32,17		19109,97243
I 70X12x26x140	80	22	31,29		20696,94471

Table 5. Estimative of materials and cost (h=150cm)

Adopted cross section	**f_{ck}- 28 days (MPa)**	**Quantity of pre stressed wires (Ø 12,7 mm)**	**Area of steel (As) (cm²)**	**Cross sectional area (m²)**	**Total cost (concrete + steel) (R$)**
I 60X14x38x150	50	28	25,09	0,4465	16660,99537
I 60X14x38x150	60	28	22,68		18596,91013
I 60X14x38x150	70	28	21,08		20322,15355
I 60X14x38x150	80	28	19,94		22106,24543
I 60X14x28x150	50	26	25,18	0,4005	15462,13316
I 60X14x28x150	60	26	23,03		17200,10167
I 60X14x28x150	70	26	21,61		18749,54419
I 60X14x28x150	80	26	20,59		20350,1593
I 70X12x21x150	50	26	20,07	0,3762	14378,50024
I 70X12x21x150	60	26	19,02		16135,05499
I 70X12x21x150	70	26	17,21		17529,5709
I 70X12x21x150	80	26	16,42		19054,57689
I 70X12x26x150	50	26	24,7	0,4052	15483,87606
I 70X12x26x150	60	26	22,26		17208,36793
I 70X12x26x150	70	26	21,08		18808,82909
I 70X12x26x150	80	26	20,24		20452,78694

Table 6. Estimative of materials and cost (h=160cm)

Adopted cross section	**f_{ck}- 28 days (MPa)**	**Quantity of pre stressed wires (Ø 12,7 mm)**	**Area of steel (As) (cm²)**	**Cross sectional area (m²)**	**Total cost (concrete + steel) (R$)**
I 60X14x38x160	50	28	17,46	0,4605	15932,55926
I 60X14x38x160	60	28	15,53		18000,2489
I 60X14x38x160	70	28	14,23		19824,38479
I 60X14x38x160	80	28	13,29		21694,57601
I 60X14x28x160	50	26	18,43	0,4145	14846,27673
I 60X14x28x160	60	26	16,43		16673,80274
I 60X14x28x160	70	26	15,27		18317,02048
I 60X14x28x160	80	26	14,44		20002,4556
I 70X12x21x160	50	26	13,27	0,3882	13720,86426
I 70X12x21x160	60	26	13,26		15670,78296
I 70X12x21x160	70	26	11,18		17082,6257
I 70X12x21x160	80	26	11,18		18760,56585
I 70X12x26x160	50	26	18,43	0,4172	14894,04375
I 70X12x26x160	60	26	15,62		16631,51622
I 70X12x26x160	70	26	14,66		18311,99062
I 70X12x26x160	80	26	13,97		20027,00651

Table 7. Estimative of materials and cost (h=170cm)

Adopted cross section	**f_{ck}- 28 days (MPa)**	**Quantity of pre stressed wires (Ø 12,7 mm)**	**Area of steel (As) (cm²)**	**Cross sectional area (m²)**	**Total cost (concrete + steel) (R$)**
I 60X14x38x170	50	26	17,88	0,4745	15837,40383
I 60X14x38x170	60	26	16,29		18018,95794
I 60X14x38x170	70	26	15,22		19933,03111
I 60X14x38x170	80	26	14,44		21884,2044
I 60X14x28x170	50	24	19,72	0,4285	14862,42166
I 60X14x28x170	60	24	17,66		16752,63957
I 60X14x28x170	70	24	16,7		18481,95664
I 60X14x28x170	80	24	16		20244,53588
I 70X12x21x170	50	24	14,59	0,4002	13705,46415
I 70X12x21x170	60	24	13,41		15566,0183
I 70X12x21x170	70	24	12,67		17201,1575
I 70X12x21x170	80	24	12,13		18861,88298
I 70X12x26x170	50	24	17,94	0,4292	14647,08772
I 70X12x26x170	60	24	16,78		16655,96232
I 70X12x26x170	70	24	15,99		18410,05339
I 70X12x26x170	80	24	15,41		20191,01006

4 CONCLUSIONS

After developing this research, the following conclusions were obtained:

- The I 70x12x21 beam presented the best structural behavior. The best structural solution (lowest cost) found was the use of this cross section with concrete compressive strength of 50MPa and 170cm of height.
- It was concluded that increasing 10cm in cross sectional height of the beams generated a reduction of approximately 30% in the necessary area of steel when this value is not close to the normative minimum.
- The use of higher concrete compressive strengths is not cost effective in the studied region (São Paulo – Brazil) since the improvement in structural performance does not result in enough steel reduction to make its cost competitive.

REFERENCES

Associação brasileira de normas técnicas, 2014. NBR 6118: Projeto de estruturas de concreto – Procedimento. Rio de Janeiro.

Associação brasileira de normas técnicas, 2017. NBR 9062: Projeto e execução de estruturas de estruturas de concreto pré-moldado. Rio de Janeiro.

Caixa Econômica Federal, 2017. *Sistema de preços, custos e índices de construção civil – SINAPI/SIPCI.* Access in: August 20th, 2017

Debernardi, P. G. & Taliano, M., 2010. Span-to-height ratio limits for prestressed concrete members. *Structural Concrete*, vol. 11, n.1, pp. 35-43.

El Debs, M. K., 2000. *Concreto pré-moldado: Fundamentos e aplicações*. EESC USP Projeto Reenge.

Turner-Fairbank Highway Research Center, 2006. *Optimized sections for high-strength concrete bridge girders – effect of deck concrete strength*. Federal Highway Administration.