

Original Research Paper

Optimization of Reinforced Concrete Beams and Steel Beams: A Comparative Study

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Abstract: In order to support the structural designer with regard to the selection of structural materials, this work presents results obtained from the optimization of reinforced concrete beams and welded “I” steel beams. To achieve this objective, both problems were formulated according to Brazilian standards, considering the cost as objective function and section dimensions as design variables. For the optimization of the proposed problems, Simulated Annealing optimization algorithm was adopted. Beams were optimized considering spans from 1 up to 25 m and two different loads. To the structures analyzed, the final costs for steel beams have always been higher than reinforced concrete, but concrete beams are significantly heavier than steel beams.

Keywords: Optimization, Steel, Reinforced Concrete, Beams, Structures, Simulated Annealing

Introduction

With the constant technological evolution and the growing competitiveness of the market, the search for projects that meet the needs of use, comfort and safety of a structure, with the minimum financial resources and environmental impact, becomes part of the engineer's daily life. In this sense, the choice of structural materials should be made based on clear criteria, considering factors such as type of work, availability of materials in the region, skilled labor and available equipment, economic costs, among others. In general, for single-family and multi-story residential buildings, the reinforced concrete structural system is prevalent. In contrast, for structures such as shopping malls, industrial pavilions or warehouses, steel structures have been widely used.

In a structural design, the designer seeks a sizing solution that meets the design's usability, comfort and safety needs while meeting the minimum requirements of technical standards. Within the wide range of possible solutions, obtaining the best-performing trial and error method based on the designer's intuition and experience becomes impractical. In this context, optimization techniques are a valuable support tool for the designer (Dede *et al.*, 2019).

According to (Rahmanian *et al.*, 2014), the optimization of structural design has been greatly driven by economic implications and the greater demand of construction to design satisfactory performance structures with reduced costs. From the point of view of (Sarma and Adeli, 2002), the ideal goal for cost

optimization should also take into account the life cycle cost of the structure, considering design, construction, operation and maintenance costs over its useful life. Additionally, in addition to the search for the global optimum, optimization can also be used to obtain alternative solutions that have not yet been imagined or tested, in order to improve the performance of the already known or previously proposed.

In order to support the structural designer with regard to the selection of structural materials, this work presents results obtained from the optimization of reinforced concrete beams and welded “I” steel beams. For increasing spans beams are compared in terms of cost, height and self-weight, using computational tools developed by the authors.

The current technical literature is rich in studies and research regarding the optimization of reinforced concrete beams (Garcia-Segura *et al.*, 2014; Rahmanian *et al.*, 2014; Kripka *et al.*, 2014; Santoro and Kripka, 2020) and steel beams (Drehmer *et al.*, 2008). However, besides the work of (Merta *et al.*, 2008), the authors do not know any study that compares elements dimensioned and optimized with these two materials.

The remainder of this paper is organized as follows. Next chapter presents the formulations to the optimization of steel beams and reinforced concrete beams. After this, some numerical simulations are presented in order to identify the main differences in relation to costs, heights and self-weight between optimized beams. Finally, some important conclusions are pointed. Among them, it was observed that, although heavier than steel beams, reinforced concrete beams led to cheaper elements to all performed simulations.

Formulations of Optimization Problems

The formulation adopted to the optimization of reinforced concrete beams was developed according to Brazilian Standard (ABNT, NBR 6118, 2014) by the third author of the present study (Medeiros and Kripka, 2013). The objective function is composed by the total cost of the beam, considering the cost of concrete (C_c), 500 MPa steel (C_{s50}) to longitudinal reinforcement, 600 MPa steel (C_{s60}) to shear reinforcement and the cost of formworks (C_f). Thus, the objective can be defined as the minimization of the function expressed in Equation (1):

$$f_{objective}(x) = (V_c \cdot C_c) + (A_{s50} \cdot L \cdot \gamma_s \cdot C_{s50}) + (A_{s60} \cdot L \cdot \gamma_s \cdot C_{s60}) + (b + 2h) \cdot L \cdot C_f \quad (1)$$

Being:

- L = Beam length
- γ_s = Steel specific weight
- B = Beam width
- H = Beam height

The constraints of the problem are listed in the sequence, where Equation (2) corresponds to neutral axis limits in relation to effective height of beam to obtain a balanced beam (in which the tension steel reaches yield strain simultaneously as the concrete reaches the failure strain); Equation (3) and (4) correspond to limits of longitudinal and transversal steel areas given by standards. Equation (5) and (6) are related to shear stresses, by comparing the working stresses respectively to compressed struts and to reinforcements in the tensioned struts. Equation (7) corresponds to bending moments. Finally, Equation (8) corresponds to the limitation to maximum displacement. Although elastic linear analysis was considered to stresses, the deformations are calculated considering cracking of concrete, in addition to long term effects:

$$0.259 < \frac{x}{d} \leq 0.628 \quad (2)$$

$$A_{s,min} \leq A_{sT} \leq A_{s,max} \quad (3)$$

$$A_{sw,min} \leq A_{sw} \leq A_{sw,max} \quad (4)$$

$$M_d \leq M_{rd} \quad (5)$$

$$V_{sd} \leq V_c \quad (6)$$

$$V_{sd} \leq V_{rd2} \quad (7)$$

$$\delta_t \leq \delta_{lim} \quad (8)$$

Being:

- x = Neutral axis
- d = Height of beam

- $A_{s,min}$ = Minimum steel area
- $A_{s,max}$ = Maximum steel area
- $A_{sw,min}$ = Minimum transversal steel area
- $A_{sw,max}$ = Maximum transversal steel area
- M_d = Acting bending moment
- M_{rd} = Resistant bending moment
- V_{sd} = Acting shear stress
- V_c = Compressed struts
- V_{rd2} = Reinforcement in tensioned struts
- δ_t = Total displacement
- δ_{lim} = Limit displacement

The height of the beam was taken as the design variable, while the width remains fixed. To the optimization of steel beams, a formulation was developed and implemented by the second author, according to Brazilian code (ABNT, NBR 8800, 2008). The objective function consists in minimizing the total cost of the beam of section A_s and length L , being C_s the steel unit cost:

$$f_{obj}(x) = A_s \cdot L \cdot C_s \quad (9)$$

Welded I-shaped profiles with double symmetry were considered, being the cross sectional dimensions the design variables, where: b_f = flange width, h = web height and t_f and t_w are the thickness of flange and web, respectively, as illustrated in Fig. 1. The constraints are described by Equations (10) to (17):

$$M_{rd} \geq M_{csd} \quad (10)$$

$$V_{rd} \geq V_{csd} \quad (11)$$

$$\delta \leq \delta_{lim} \quad (12)$$

$$150mm \leq d \leq 2.000mm \quad (13)$$

$$6.35mm \leq t_f \leq 50mm \quad (14)$$

$$4.75mm \leq t_w \leq 50mm \quad (15)$$

$$b_f \leq d \leq 4b_f \quad (16)$$

$$t_w \leq t_f \quad (17)$$

Being:

- M_{rd} = Resistant bending moment
- M_{ced} = Acting bending moment
- V_{rd} = Resistant shear stress
- V_{csd} = Acting shear stress
- δ = Maximum displacement
- δ_{lim} = Limit displacement
- d = Total height
- t_f = Flange thickness
- b_f = Flange width
- t_w = Web thickness

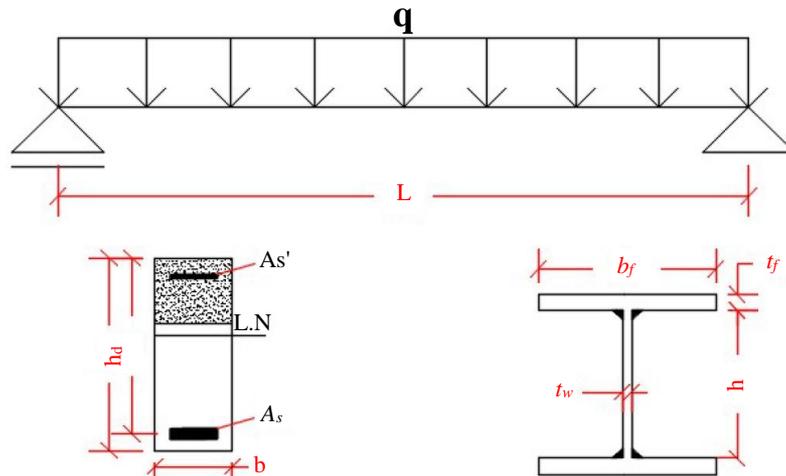


Fig. 1: Problem studied

The constraints described by Equation (9) to (11) correspond to the verification of ultimate limit states, where the strength to bending moment M_{rd} and shear stress V_{rd} must be greater or equal their corresponding acting stresses M_{csd} and V_{csd} . Equation (12) corresponds to maximum displacement limitation. Equation (13) consists in a manufacturing limitation related to welding process. Equation (14) and (15) fix lower and upper thickness limits to available market values. Finally, Equation (16) and Equation (17) limit the section dimensions according to the standard (ABNT, NBR 5884, 2000).

Both formulations were implemented by the usage of Simulated Annealing optimization algorithm. Simulated Annealing is a heuristic method developed in analogy of the mechanical process of annealing applied to metals. This method, originally proposed by (Kirkpatrick *et al.*, 1983), has as main advantage the reduced number of control parameters regarding other widely used methods such as genetic algorithms, particle swarm and harmony search (Kripka, 2004).

Once only simply supported beams were considered, the stresses and displacements were obtained directly from analytic expressions.

Numerical Simulations

Problem Studied

The formulations were applied to the dimensioning of simply supported beams with different spans. It was considered a uniform load over the span length L , composed by dead load of 16KN/m and live load of 7KN/m. Self-weight was automatically computed and added to dead loads.

The costs considered to materials were the following: cost of concrete f_{ck} 30MPa: US\$ 91.21/m³, cost of steel 500 MPa: US\$ 1.47/Kg, cost of steel 600 MPa: US\$ 2.00/Kg and cost of formworks: US\$ 22.15/m².

For the cost of concrete, the costs of launching with a pump truck, density and finishing were considered. Likewise, the cost of steel is composed of the value of the material and also the labor and other items necessary for cutting, bending and assembling a structural element. Because this study is working only with the steel area, without considering the diameters to be used, the average market value to steel bars was adopted, for gauges ranging from 6.3 to 20 mm. The cost of the formwork takes into account the value of the material and the labor (sawn wood and metallic support). The reuse of formwork was also considered. For the steel profiles, the unit cost of the finished metallic structure, in "I" profile, was considered. The cost composition takes into account the supply of steel sheets, materials and inputs for the execution of welding and assembly, including labor.

Optimum Cost of Reinforced Concrete Beams

To the adopted formulations, simply supported beams were analyzed considering minimum and maximum loads and spans ranging from 1 to 25 m. The beam width was fixed as 15 cm.

At first, the design was made limiting the displacements for effects on non-structural elements ($L/350$), according to NBR 6118: 2017. The optimal cost is illustrated in Fig. 2. It can be observed that the difference in the optimal cost regarding minimum and maximum loads is lower than 15% and that the optimized dimensioning had the displacements limitation as the active constraint for all spans and loads.

The height that leads to the optimum cost of the beam has the behavior of a polynomial function of degree 2, as shown in Fig. 3. For the minimum load, the average for the height/span ratio was approximately 11 to spans from 1 to 12 m, while for 13 to 25 m the average ratio was 15. At maximum load, the ratio is slightly higher, being 14 for the first interval and 18 for the second.

In the composition of the total cost, formwork represents the highest percentage in relation to the final cost (about 65%), followed by concrete and steel, respectively. In an alternative situation, the cost of formwork was considered as US\$ 15.92, corresponding to 6 reuses instead of 2, as originally adopted. For this consideration, naturally the total cost was slightly lower and consequently the representativeness of the formworks decreased to values below 60% in relation to the total cost. Nevertheless, this variation didn't generate any change in the optimized dimensions of the beam.

Optimum Cost of Steel Beams

Similar to reinforced concrete beams, steel beams were optimized for increasing spans from 1 to 25 m. Fig. 4 illustrates the optimized costs corresponding to the loads and spans considered.

Contrary to reinforced concrete beams, the displacements were not the active constraints for the spans considered. The optimal height of the sections varied from between 8 to 4% of the span, with the lowest ratio for larger spans Fig. 5.

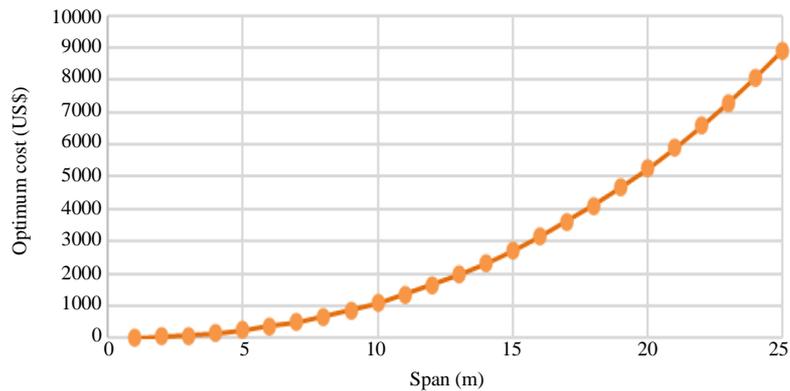


Fig. 2: Optimum cost to RC beams

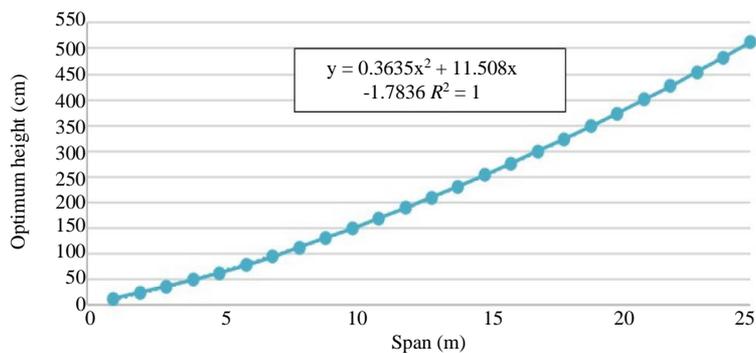


Fig. 3: Optimum section height

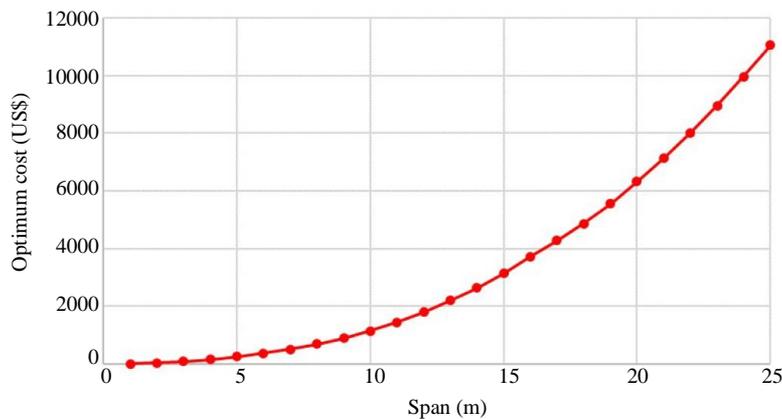


Fig. 4: Optimum cost to steel beams (I profile)

Comparison of Reinforced Concrete Beams and Steel Beams

The optimal cost obtained through the optimized design for both types of beams generated a very similar behavior, as can be seen in Fig. 6. Figure 7 illustrates the difference between steel cost and reinforced concrete cost. It can be noticed that for small spans the optimized cost doesn't represent significant differences for the different types of beam. On the other hand, for largest span the steel beam is almost 25% more expensive than

the reinforced concrete beam. Regarding the optimized heights Fig. 8, the differences are quite expressive, especially for spans over 10 m.

Figure 9 shows the self-weight of beams, where a huge difference between the self-weight for the different types of beam can be observed. Reinforced concrete beams were much heavier than the steel ones, reaching differences greater than 6 times for the largest spans. For spans of less than 10 m the self-weight has less expressive differences, but is still quite significant.

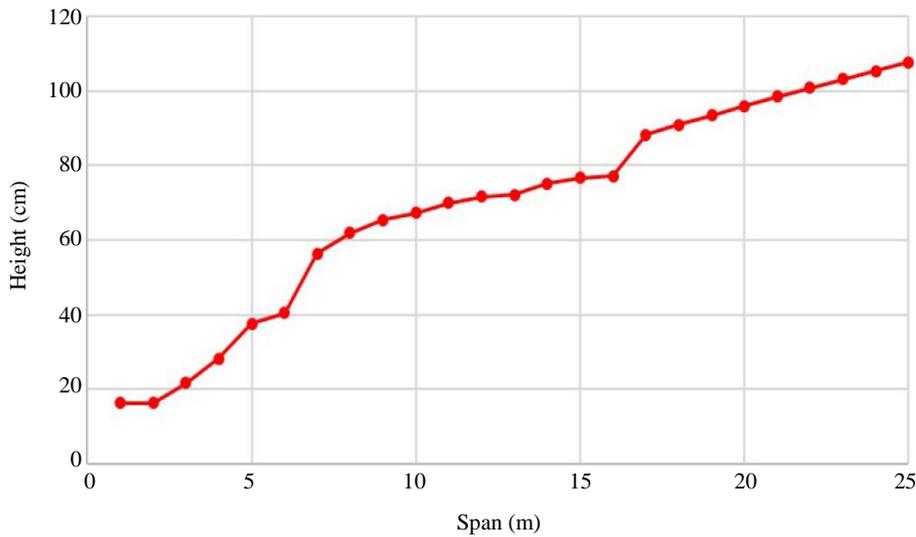


Fig. 5: Optimum height to steel beams

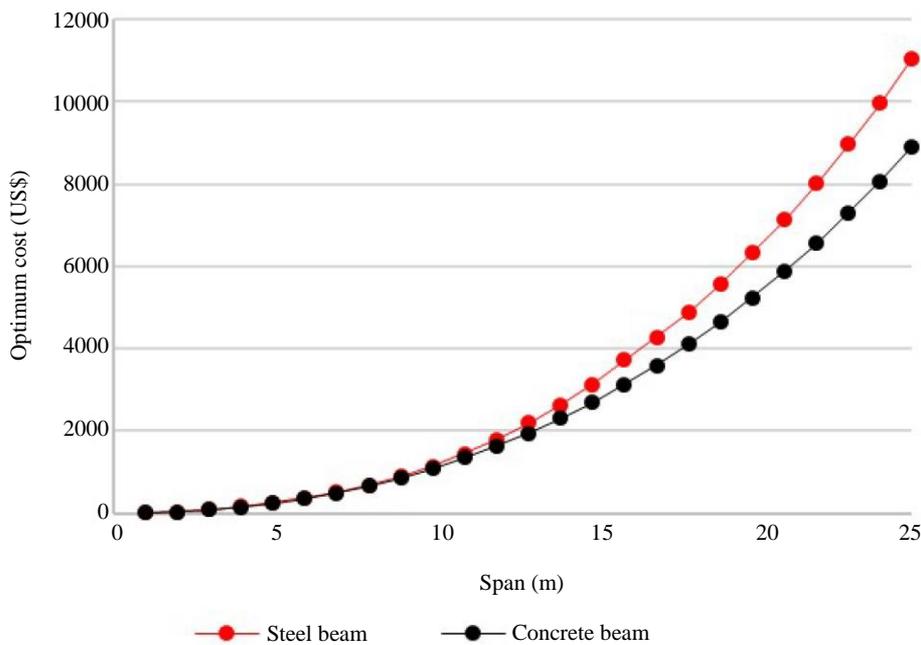


Fig. 6: Optimum cost (steel x concrete)

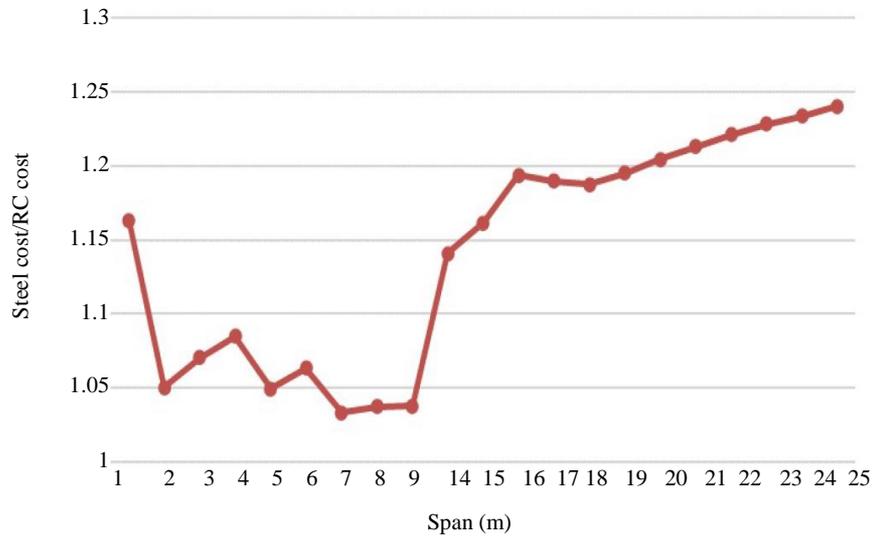


Fig. 7: Optimum relative cost (Steel/RC)

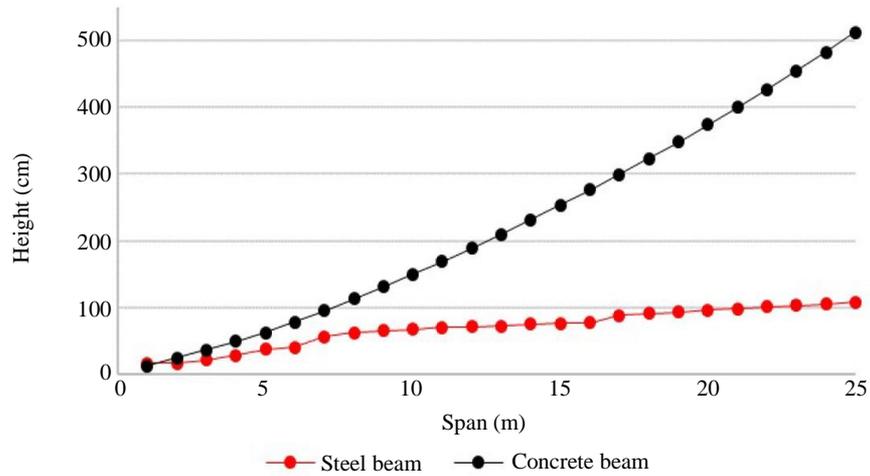


Fig. 8: Optimum height (steel × concrete)

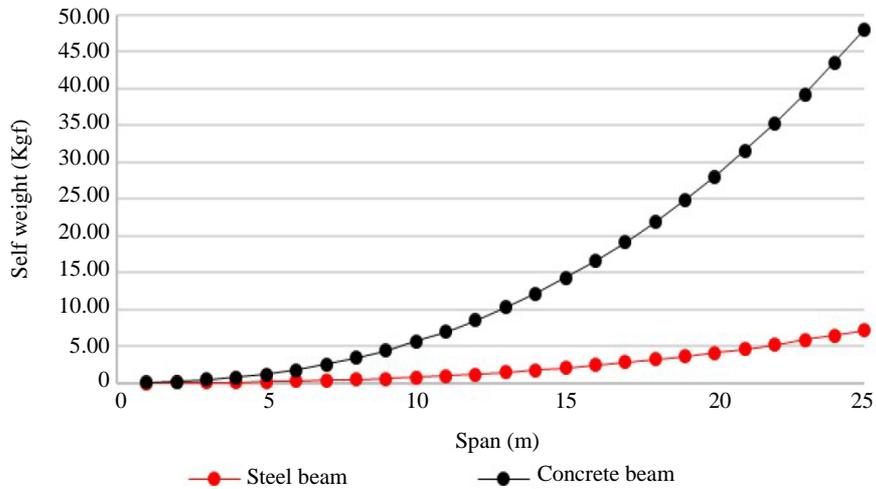


Fig. 9: Self weight (steel × concrete)

Conclusion

The present work aimed a comparative study between the optimized design of reinforced concrete and steel beams. To achieve this objective, both problems were formulated according to Brazilian standards, considering the cost as objective function and section dimensions as design variables. For the optimization of the proposed problems, Simulated Annealing optimization algorithm was adopted. Beams were optimized considering spans from 1 up to 25 m and two different loads. Based on the results, it was observed that the optimal cost behavior for reinforced concrete and steel beams was quite similar for spans up to 25 m. The final costs for steel beams have always been higher than reinforced concrete. In general, for spans of up to 10 m the difference is not significant, increasing for larger values. For the largest span studied (25 m) the concrete beam was 19% cheaper compared to steel. On the other hand, concrete beams are significantly heavier than steel beams, regardless the span considered. In addition, it was observed that, when the height of the beams is an important aspect to be considered, steel beams consists in a good option.

In general, it can be seen that a given material, when compared to others, presents positive and negative characteristics. In this sense, a more comprehensive study considering other aspects by using multi-criteria decision-making methods as in (Kripka *et al.*, 2019), is being performed.

Although the present study considered only simply supported beams, similar methodology can be used to compare other structural materials, configurations and elements. In addition, other aspects such as labor costs can be considered. Despite Brazilian standards were adopted, it can be supposed that the results are valid to other design codes.

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Author's Contributions

Joel M. Ozimboski: Numerical simulations, manuscript preparation.

Zacarias M.C. Pravia and Moacir Kripka: Computational implementation, manuscript preparation.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of

the other authors have read and approved the manuscript and no ethical issues involved.

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