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Vicinal bridge design with high-strength steels and built-up sections

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Abstract

Steel has become a very promising alternative for structural systems of bridges, mostly due to the simplification of the erection process related with prefabrication and aligned with adequate strength and stiffness, leading to an improved efficiency of the overall set of beams, columns and cables. Nevertheless, the first national Brazilian design code for steel and composite bridges was only approved in 2020 as ABNT NBR 16694, providing guidelines based on ABNT NBR 8800:2008. Whereas both standards allow for the use of steels with yield strength up to 450 MPa, national market is still oriented towards average grades such as 36 or 50, neglecting savings in costs and materials associated with the use of high-strength steels (HSS). As such, this paper assesses the application of such steel grades in composite vicinal bridges through a parametric study varying both the span length and the steel grade, but also by taking advantage of built-up sections, custom made designed. Furthermore, on account of certified steels, carbon emissions were estimated, for each scenario, based on the relevant Environment Product Declaration (EPD) which is the starting point for life-cycle analysis (LCA). Results showed that HSS are performant for this application and are, in meanwhile, aligned with sustainable development principles.

Keywords: bridge design; high-strength steels; environment product declaration; cost analysis.

1. Introduction

According to the Australian Steel Institute (2021), high-strength steels (HSS) are a promising alternative solution for all kinds of engineering problems, even in construction field. Depending on the arrangement, weight savings can reach more than 30% in structures, allowing for designs with longer spans, higher load-carrying capacity, reduction in foundations costs and also good formability and weldability.

In general, minimum yield strength is the main decision driver when classifying a steel as HSS. For example, in Europe, hot-rolled sections, classified as HSS (ARCELORMITTAL, 2021), are eligible to be fabricated in ASTM A913 grades 65, 70 and 80 ksi thanks to Quenching and Self-Tempering (QST) process. In Australia, market surveys reported the used of up to 690 MPa steels in construction as well as in mechanical engineering space (AUSTRALIAN STEEL INSTITUTE, 2021). Nevertheless, since Brazilian National Design Code NBR 8800 (ABNT, 2008) currently limits the application of steel grades up to 450 MPa in structures of buildings and combined with current market practices of application of 50 ksi steels, the range 400~450 MPa is suggested as HSS due to present national practice.

Additionally, the use of built-up sections from steel plates can bring an edge to the design of buildings since the geometry of the profiles is defined according to each project, comprising, for example, boxes, channels and I-sections. Also, as plates can be obtained from hot-rolled coils (HRC) and fabricated in several grades and patterns, structural engineers have a wider portfolio at their disposal when selecting the most appropriate material. In this context, Rasmussen and Hancock (1995) assessed the experimental behavior of welded columns with 690 MPa of nominal yield strength from flame-cut process to select the appropriate curve from the Australian steel structure. At that time, their results showed agreement with the American, Australian and British standards, being Eurocode 3 the only exception for conservatively predicting resistance.

At the same time, society moves towards sustainability to take into account the impacts on human lives. According to Eberhardt *et al.* (2021), construction segment requires, on average, 40% of energy to industrialize components and 60% of minerals from Earth, enhancing the emission of Green House Gases (GHG) and producing almost 40% of the solid waste measured in the world. Therefore, steel appear as a promising construction material due to its recyclability and reuse potential as shown in Figure 1.

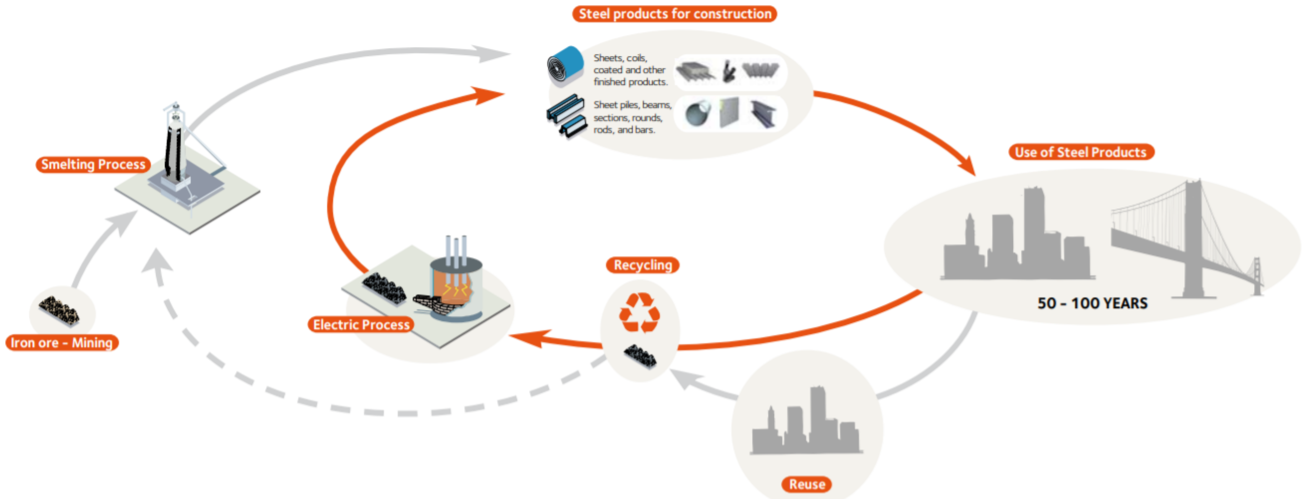

Figure 1 – Sustainable cycle of steel.
Source: Our Steel solutions for your Green Building (ARCELORMITTAL, 2021).

It is important to state that the gains arisen from green steels can be extracted from their Environmental Product Declaration (EPD), which is issued as per international standard ISO 14025 (ISO, 2006). It contains the sustainable performance of HRC for boundaries A1-A2-A3 (raw material supply, transport, manufacturing), C3 (waste processing) and D (reuse-recovery-recycling potential) according to IBU (2020). Hence, it is easy to quantify the cumulative impacts considering exclusively the steel fabrication process, not considering the industrialization process into welded sections.

Thanks to the approval of first national Brazilian design code for steel and composite bridges NBR 16694 (ABNT, 2020), this paper aims to assess the mechanical performance of HSS (up to 450 MPa as recommended by NBR 8800 (ABNT, 2008)) and to compare the unit steel consumption with the standard grade (345 MPa). Simultaneously, environmental performances in terms of carbon dioxide emissions and use of fresh water are presented, ensuring the benefits of HSS.

2. Design of composite beams according to ABNT NBR 8800:2008

In this paper, only full composite action is taken into account in large spans intended for simply supported bridge beams. Furthermore, NBR 8800 (ABNT, 2008) recommends that minimum interaction degree must be taken as 1,0 ($\eta_{min} = 1{,}0$) for spans over 25,0 m in case of symmetric profiles or over 20,0 m in case of monosymmetric ones.

2.1 Bending resistance of simply supported beams

Firstly, considering relative slenderness of web and consequent absence of local buckling $\left(h/t \leq 3{,}76\sqrt{E/f_y}\right)$ of compact sections, stresses follow plastic distribution until first plastic hinge. Depending on the geometry and material properties, plastic neutral axis can be either on the beam web, the beam flange or the concrete slab, according to Figure 2.

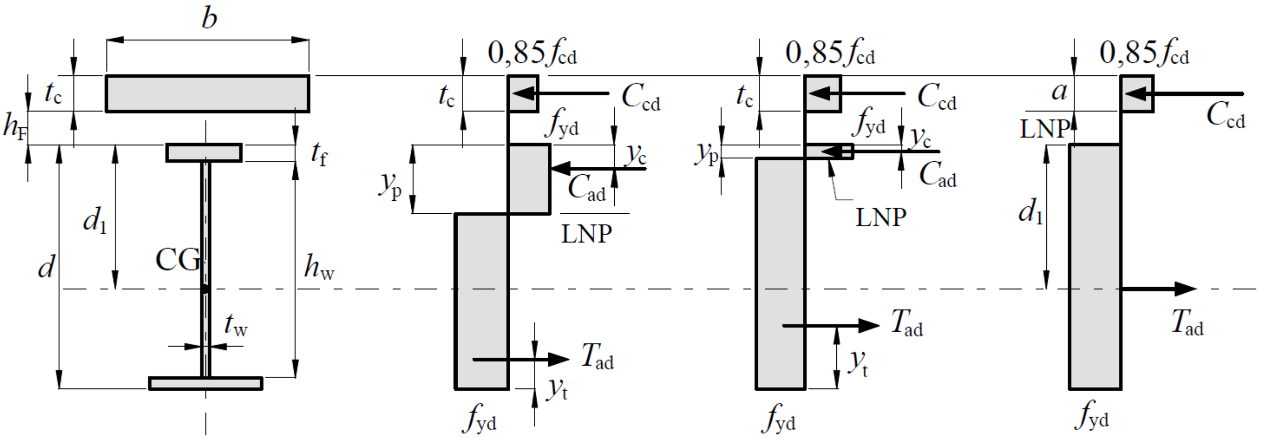

Figure 2 - Stress distribution in compact composite beams under sagging moment.
Source: NBR 8800 (ABNT, 2008).

If the concrete resistance exceed steel's – $0{,}85f_{cd}bt_c \geq A_a f_{yd}$, in which f_{cd} is the concrete design compressive strength, b is the slab effective width, t_c is the slab thickness, A_a is the section gross area and f_{yd} is the design yield strength, the bending resistance M_{Rd} should be determined in accordance with Eq. (1) and Eq. (2).

$$a = \frac{A_a f_{yd}}{0{,}85 f_{cd} b} \leq t_c \qquad \text{Eq. (1)}$$

$$M_{Rd} = A_a f_{yd} \left(d_1 + h_F + t_c - \frac{a}{2} \right) \qquad \text{Eq. (2)}$$

Then, if the plastic neutral axis lays on steel profile ($A_a f_{yd} \geq 0{,}85 f_{cd} b t_c$), M_{Rd} must be calculated as indicated by Eq. (3) to Eq. (7):

$$C_{cd} = 0{,}85 f_{cd} b t_c \qquad \text{Eq. (3)}$$

$$C_{ad} = \frac{1}{2} \left(A_a f_{yd} - C_{cd} \right) \qquad \text{Eq. (4)}$$

$$T_{ad} = C_{cd} + C_{ad} \qquad \text{Eq. (5)}$$

$$C_{ad} \leq A_{af} f_{yd} \therefore y_p = \frac{C_{ad}}{A_{af} f_{yd}} t_f \qquad \text{Eq. (6)}$$

$$C_{ad} > A_{af} f_{yd} \therefore y_p = t_f + h_w \left(\frac{C_{ad} - A_{af} f_{yd}}{A_{aw} f_{yd}} \right) \qquad \text{Eq. (7)}$$

In which C_{cd} is the compression force in concrete slab, C_{ad} is the compression force in the steel profile, T_{ad} is the tension force in steel profile, A_{af} is the area of the top flange, y_p is the centroid position of the section under compression, t_f is the flange thickness and A_{aw} is the web area.

Finally, for non-compact webs $\left(3{,}76\sqrt{E/f_y} < h/t \leq 5{,}70\sqrt{E/f_y}\right)$, the bending resistance must be calculated in elastic regime by limiting the stresses on the concrete flange to f_{cd} and, meanwhile, in the bottom flange to f_{yd} according to Eq. (8) and Eq. (9), respectively.

$$\sigma_{cd} = \frac{M_{sd}}{\alpha_E (W_{tr})_s} \qquad \text{Eq. (8)}$$

$$\sigma_{td} = \frac{M_{sd}}{(W_{tr})_i} \qquad \text{Eq. (9)}$$

Where α_E is modular ratio (quotient between steel and concrete modulus of elasticity).

2.2 Shear resistance

According to NBR 8800 (ABNT, 2008), the shear force must be withstand exclusively by web. Hence, considering the ultimate limit states of shear buckling or yielding due to shear stress. Since $V_{pl} = 0{,}60 d t_w f_y$, where d is section height, t_w is web thickness and f_y is steel yield strength, V_{Rd} must be considered according to Eq. (10) to Eq. (13):

$$\lambda = \frac{h}{t_w} \qquad \text{Eq. (10)}$$

$$\lambda_p = 1{,}10\sqrt{\frac{k_v E}{f_y}} \qquad \text{Eq. (11)}$$

$$\lambda_p = 1{,}37\sqrt{\frac{k_v E}{f_y}} \qquad \text{Eq. (12)}$$

$$V_{Rd} = \begin{cases} \dfrac{V_{pl}}{\gamma_{a1}} & \lambda \leq \lambda_p \\ \dfrac{\lambda_p}{\lambda}\dfrac{V_{pl}}{\gamma_{a1}} & \lambda_p < \lambda \leq \lambda_r \\ 1{,}24\left(\dfrac{\lambda_p}{\lambda}\right)^2 \dfrac{V_{pl}}{\gamma_{a1}} & \lambda > \lambda_r \end{cases} \qquad \text{Eq. (13)}$$

In which γ_{a1} is the partial shear resistance for buckling or yielding, taken as 1,10.

2.3 Unpropped construction

Since bridge structural elements can be prefabricated and erected in the construction site, steel beams must withstand to all dead and live loads before concrete reaches $0{,}75f_{ck}$, in which f_{ck} is the characteristic compressive strength. Furthermore, in the case of beams with non-compact webs $\left(3{,}76\sqrt{E/f_y} < h/t \leq 5{,}70\sqrt{E/f_y}\right)$, Eq. (14) must also be satisfied.

$$\left(\frac{M_{Ga,Sd}}{W_a}\right) + \left(\frac{M_{L,Sd}}{W_{ef}}\right) \leq \frac{f_y}{\gamma_{a1}} \qquad \text{Eq. (14)}$$

in which $M_{Ga,Sd}$ is the bending moment on the steel beam before the concrete reaches $0{,}75f_{ck}$, W_a is the elastic modulus of the bottom flange, $M_{L,Sd}$ is the bending moment on the composite beam after the concrete reaches $0{,}75f_{ck}$, W_{ef} is the elastic module of the composite section, f_y is the yield strength of the steel beam and γ_{a1} is the partial shear resistance for buckling or yielding, taken as 1,10.

2.4 Deflection

According to NBR 8800 (ABNT, 2008), the displacements are calculated based on the transformation of composite section based on modular rate $\alpha_E = E_a/E_c$, where E_a and E_c are steel and concrete modulus of elasticity, disregarding contributions of concrete under tension. Finally, creep and shrinkage must also be considered for long term actions by reducing the value of E_c with a factor of 1/3, which increases α_E to $3\alpha_E$. Maximum deflection is obtained according to Eq. (15) as suggested by Fakury, Silva and Caldas (2016).

$$\delta_{max} = \delta_{p,pa} + \delta_{p,ld} + \delta_{v,cd} + \delta_{v,ld} - \delta_{p,te} - \delta_c \leq \frac{L}{800} \qquad \text{Eq. (15)}$$

in which δ_{max} is the maximum displacement of the beam, $\delta_{p,pa}$ is the displacement on construction stage considering exclusively the steel profile, $\delta_{p,ld}$ is the displacement of permanent loads (long duration), $\delta_{v,cd}$ is the displacement of the variable loads (short duration), $\delta_{v,ld}$ is the displacement of the variable loads (long duration), $\delta_{p,te}$ is the displacement of the steel beam, eliminated after concrete curing and δ_c is the imposed displacement applied in the steel beam.

3. Methods

The study proposed herein consists in the design of a simply supported composite highway bridge, with the cross section presented in Figure 3, which is a popular model applied for vicinal roads in Brazil (CBCA, 2007). Two main steel beams are positioned under a composite (steel and concrete) slab with the steel deck Polydeck 59S, manufactured by Perfilor with 1,25 mm thick steel plate. Its total depth is adopted as 25 cm.

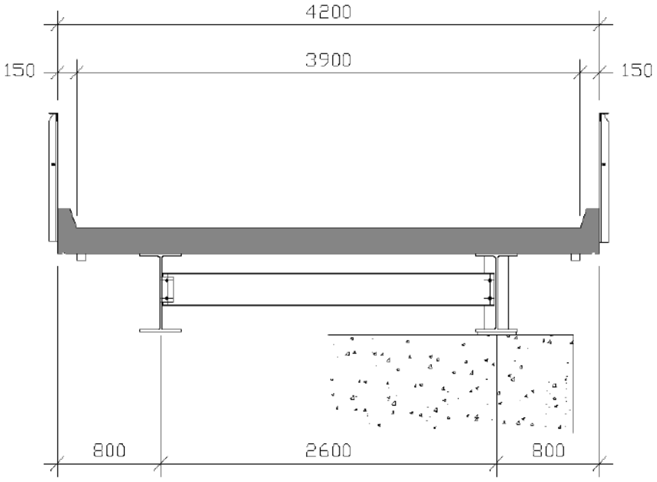

Figure 3 – Cross section of popular bridges in Brazil.
Source: CBCA composite bridges manual (PINHO E BELLEI, 2007).

In addition, the following loads were taken into account in the design and the combination factors were chosen according to NBR 16694 (ABNT, 2020):

a) dead load of the steel beams and connections plates, taken as 5% of steel weight (specific weight: $\gamma_s = 78{,}5\ kN/m^3$);
b) dead load of the slab: $q_{slab,k} = 5{,}35\ kN/m^2$ (ARCELORMITTAL PERFILOR, 2016);
c) dead load of 15-cm-concrete layer over the slab: $q_{layer,k} = 3{,}75\ kN/m^2$;
d) lateral defenses: $q_{defense,k} = 0{,}47\ kN/m$;
e) live load due to traffic: TB-45, according to NBR 7188 (ABNT, 2013);
f) live load of 1 kN/m^2 in construction phase, removed after concrete curing.

During construction, when lateral torsional buckling may occur, the steel beams are laterally restrained each 5 m and consequently the unbraced length must be taken as $L_b = 5{,}0\ m$.

Consequently, four isostatic spans ($6\ m$, $12\ m$, $15\ m$ and $20\ m$), referred as L, and three steel grades ($345\ MPa$, $400\ MPa$ and $450\ MPa$), referred as f_y, were analyzed. The steel consumption, equivalent carbon dioxide emissions and water usage were assessed for all 12 models, considering contributions arisen from steel production phase (ARCELORMITTAL, 2020) and concrete. For all cases, the sections are optimized to minimize steel consumption, leading to a coefficient of utilization as close as possible to 1,0.

4. Results and discussions

As expected, the use of HSS in the vicinal bridge structure, as shown in Figure 3, led to savings in steel consumption of main beams. Figure 4 reports the percentual steel weight for all the assessed models (reference value $f_y = 345\ MPa$) grouped by span length. The values obtained for each case highlight savings from 8 to 19% for $f_y = 400\ MPa$ and from 12 to 25% for $f_y = 450\ MPa$.

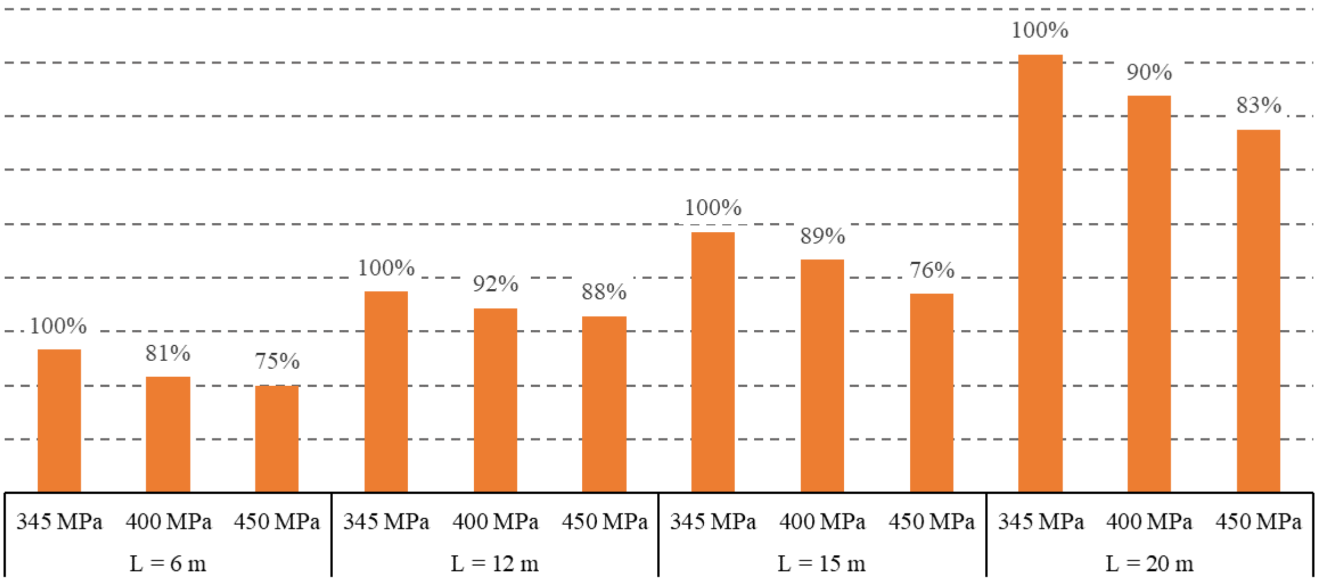

Figure 4 – Economy in steel consumption of assessed models.
Source: Authors.

Meanwhile, Figure 5 confirm the sustainable benefits arisen from the use of HSS in structures. Due to the savings is steel consumption, less CO_2 equivalent is generated during the fabrication process of HRC, used afterwards in the fabrication of the sections. The emissions from the concrete are the same in all cases since the concrete volume remain constant in all the models, which allows for the assessment of the contributions of the steel beams alone.

It’s important to state that recyclability and reuse potentials of steel at the end of its life also provide reductions in CO_2 creation, which is not applicable to concrete structures (the slab in this case) and that is the reason why concrete is the main source of greenhouse gases in these examples – more than 50% in 75% of cases. Similar remarks are also valid for the use of fresh water, for which savings are ranged between 3 and 6% owe to economies in global steel consumption.

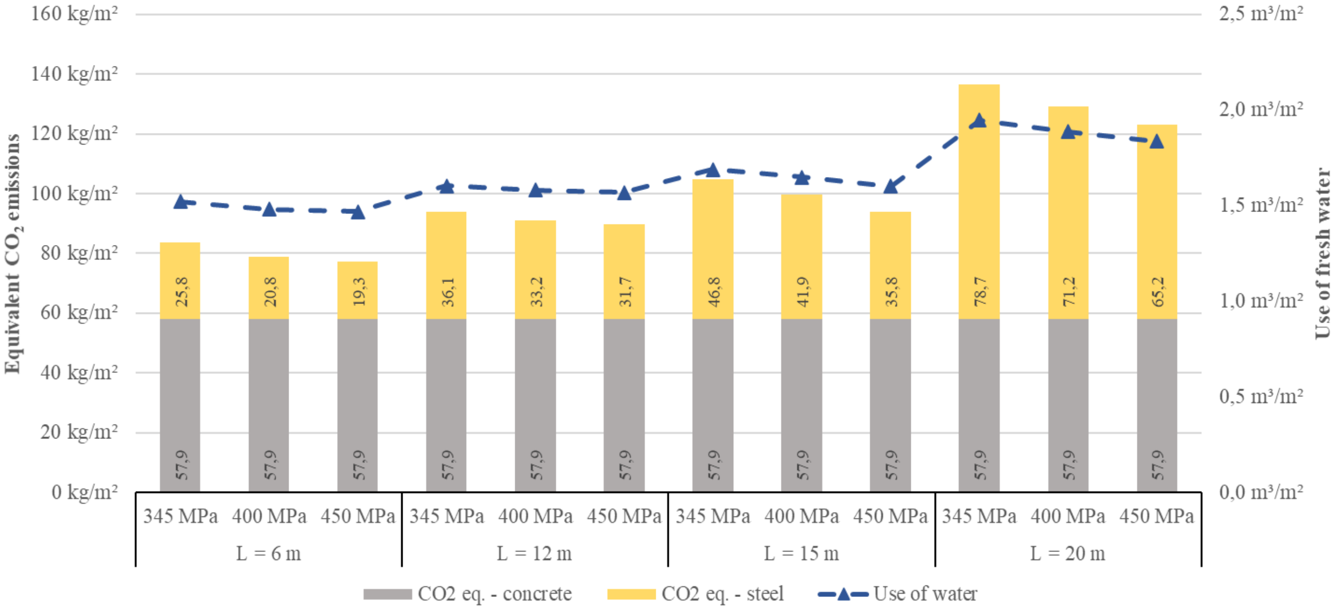

Figure 5 – Equivalent CO_2 emissions and fresh water use during steel and concrete production.
Source: Authors.

5. Conclusion

The following conclusions can be drawn from the present article:

- As previously stated by the Australian Steel Institute (2021), high-strength steels are becoming a promising alternative in civil construction, bringing average savings of about 30% to columns and beams. In case of bridges, this paper proposed to assess the mechanical performance of HSS when applied to vicinal bridges, using typical geometries from Brazilian market. As such, four spans were tested, which represent most of the bridges built in Brazil, however designed with beams with different steel grades, keeping constant all remain variables (span, concrete mechanical properties and slab geometry, for example). As observed, an increase in the steel yielding strength from 345 to 450 MPa (current upper limit allowed by NBR 16694 (ABNT, 2021) and NBR 8800 (ABNT, 2008)), can reduce the steel consumption in the composite bridge from 12% to 25%. These values are in accordance with Australian Steel Institute (2021) market data.

- A consequence of the reduction in the steel consumption in the superstructure, is the problable reduction of the correspondent dead loads in the foundations. Hence, less materials such as concrete, rebars and foundation piles are needed, which might decrease the total cost of the project.

- Sustainability is not only a differential in construction market, but a decision driver in the selection of the best structural system. Considering the current needs to reduce the emissions of greenhouse gases and to use recyclable/reusable components, HSS stands as a promising choice, reducing 10%, on average, the equivalent carbon dioxide emissions during fabrication of structural components (steel and concrete) - mostly due to concrete - as well as fresh water consumption.

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