VALUTAZIONE DELLA SOSTENIBILITÀ DI ELEMENTI IN ACCIAIO ALTO RESISTENZIALE

SUSTAINABILITY ASSESSMENT OF HIGH STRENGTH STEEL ELEMENTS

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ABSTRACT

The concern for environmental awareness is currently growing more and more. The last message from the IPCC (Intergovernmental Panel on Climate Change) was clear, significant actions are mandatory and urgent to achieve the objective to limit global warming to 1.5°C. The building sector is one of the most polluting industrial sectors for which solutions must be found to cut the emissions. The development of new production technologies can contribute to this aim by creating innovative and more sustainable materials. Amongst the new materials that appear on the steel market, high strength steels are a nice example as they offer the highest strength to weight ratio of any structural steel, resulting in material savings, lighter foundations, easier transportation, and erection. These multiple advantages explain why the use of high strength steels could lead to significant carbon emission savings. However, the production of such steels uses more alloying elements and sometimes they require more energy than for regular grades. The aim of this paper is to estimate the Global Warming Potential of high strength steels to evaluate whether they constitute sustainable materials. This paper demonstrates that, in many cases, the increase of carbon emissions as function of yield strength can be neglected, which leads to an environmental benefit in using high strength steels.

SOMMARIO

La crescita di consapevolezza circa la gravità e l'impatto della crisi climatica è sempre maggiore. L'ultimo messaggio dell'IPCC (Intergovernmental Panel on Climate Change) è stato chiaro, per raggiungere l'obiettivo di limitare il riscaldamento globale a 1,5°C servono azioni significative immediate. Il settore delle costruzioni è uno dei settori industriali più inquinanti, occorre trovare soluzioni per ridurre l'impatto del settore sulle emissioni globali. Lo sviluppo di nuove tecnologie di produzione può contribuire a questo obiettivo mettendo sul mercato materiali innovativi e più sostenibili. tra differenti possibilità e e innovazioni della filiera dell'acciaio, troviamo gli acciai ad alta resistenza, che sono un esempio di come ottimizzare il materiale utilizzato porta a notevoli benefici. Questi acciai offrono il più alto rapporto resistenza/peso di qualsiasi acciaio strutturale, con conseguente risparmio di materiale, fondazioni più leggere, trasporto ottimizzato e velocità di montaggio. Questi molteplici vantaggi spiegano perché l'uso di acciai ad alto resistenziali potrebbe portare a significativi risparmi di emissioni di carbonio. Tuttavia, la produzione di tali acciai utilizza più elementi di lega e talvolta richiede più energia rispetto ai gradi normali. Lo scopo di questo documento è di stimare il potenziale impatto ambientale degli acciai ad alta resistenza e fare delle considerazioni sulla loro sostenibilità ambientale. Questo lavoro dimostra che, in molti casi, l'eventuale aumento di emissioni di carbonio in funzione del limite di snervamento dell'acciaio può essere trascurato, portando ad un beneficio nell'utilizzo di acciai ad alta resistenza.

1. INTRODUCTION

Nowadays, the notions of sustainability and resilience from an economic and an environmental point of view are becoming more and more important subjects considering that the Earth's resources are not inexhaustible, and that the climate challenges of tomorrow's world become crucial to ensure the best possible lifestyle for future generations. In this context, all professional sectors are trying to adapt their operating methods to reduce their emissions and their waste. In particular, the construction sector is considered to have a considerable impact in terms of pollution. Indeed, according to the global status report for buildings and construction [1], it is responsible of 36% of global energy demand and 37% of energy-related CO_2 emission. The way we build must be modified by optimizing the future structures i.e., choosing the most appropriate material to realize material savings, improving the production process to reduce energy consumptions, designing in a way that respects the circular economy concept (reducing, reusing, remanufacture and recycling) [2]. All these actions are becoming compulsory to reach carbon neutrality by 2050, as stipulated in the Paris agreement [3].

Amongst building structural solutions, significant improvements can be observed in the field of steel structures allowing for a progressive decarbonisation of the production processes but also for an increase of the yield strength and consequently, for a reduction in the weight of structures. According to the World Steel Association [4], over 75% of the 3500 steel grades in use today did not exist 20 years ago. In 1937, 83000 tonnes of steel were needed to make the Golden Gate Bridge. Today, ½ of that amount would be required. If the Eiffel Tower were to be rebuilt today, the engineers would only need one-third of the steel that was originally used. Substituting regular steels for advanced high strength steels makes it possible to build high-rise buildings with 50% less steel compared to the amount needed 50 years ago. For automotive industry, the use of advanced high strength steels leads to even a higher benefit given the consumption savings generated by the reduction of the vehicle weight during the use phase of the material life cycle.

Indeed, when the resistance of the material is the dimensioning criterion, the yield strength increase will lead to a substantial gain in material usage by drastically reducing the section dimensions. Less material also means lower environmental impact but also indirect benefits, such as cost savings for building foundations, reduced transportation, a greater speed of construction, and therefore reduced cost and reduced environmental burden. However, the execution of more slender structures is often associate with instability problems or excessive deflections. These aspects, essential in civil engineering, can sometimes limit the potential interest in using these grades [5], [6].

Considering some production techniques for high strength steels, which are sometimes more CO_2 emitting in terms of energy consumption, as well as more demanding in terms of alloy content, the cost, and the global warming potential (GWP) generally increase with the yield strength. However, for a circular design, one must consider a life cycle approach, including in a possible comparison all phases (from extraction of raw material to end of life) and considering already mentioned benefits in design (weight reduction, cost saving, etc). Based on this observation, the following question can be raised: where is the interest, from an economic and environmental point of view, in using high strength steels in civil engineering? This publication will reflect first investigations initiated at the University of Liège regarding the environmental aspect while the economic benefit has already been treated in another paper [5]. In this paper, a literature review has been performed regarding the evolution of carbon emissions as function of the yield strength. A methodology is then proposed to estimate carbon emissions of high strength steels in order to compare the relative carbon emissions to the weight savings generated by using high strength steels.

2. BACKGROUND ON GWP AS FUNCTION OF YIELD STRENGTH

The global warming potential (GWP) in the process of metal production is a conversion factor to compare the influence of different greenhouse gases on the climate system. The GWP depends on:

- the steel production route - Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF) are the two main routes nowadays [4];
- the steel production process - As rolled (AR), Normalized (N), Thermo-mechanically rolled (M) and quenched and tempered (Q);
- the chemical compositions of the steel - alloys have a major impact on the environmental footprints of steels.

Specific information relating to a construction material or product is disseminated using Environmental Product Declarations (EPD). These standardized documents contain quantitative data on the environmental impact of a product for its entire life cycle such as global warming potential, smog creation, ozone depletion and water pollution. They are produced based on Life Cycle Assessment (LCA) calculations according to requirements of ISO14025 [7] and EN15804 [8] standards. However, these declarations are generally done by steel manufacturer directly or by Associations, e.g. Bauforumstahl, Asociación Sostenibilidad Siderúrgica. For example, in the Bauforumstahl EPD ([9]), the following sentence appears: *"This EPD is valid for structural sections and merchant bars of various steel grades and different forms of delivery".* In other words, it means that the available EPDs on the market are not providing or very partially GWP values depending on steel grade. Given these reference documents do not provide any information regarding the evolution of carbon emissions as a function of yield strength, the literature has been browsed to see if other authors have established a relationship between the environmental impact and the yield strength.

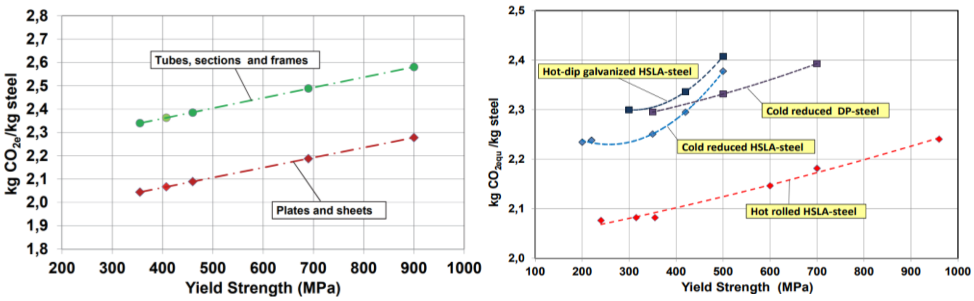
2.1 Evolution of the CO_2 emissions

A project called "The environmental value of HSS structures" has been already conducted within the framework of the Steel Eco-Cycle project (2004-2012) [10]–[13]. In this project, the Swedish steel industry carried out a series of cradle-to-gate analyses in collaboration with the Swedish Environmental Research Institute and provide carbon emission evolutions as function of yield strength and depending on the steel typology (Fig. 1). The Gabi database was used to get general data such as alloying elements as well as transportation requirements to establish the reported evolutions in Fig. 1.

It is worth pointing out that "sections" terminology refers to cold-formed hollow sections (EN10219) as hot-rolled sections do not yet exist for yield strengths higher than 500MPa in Europe and 80ksi (550MPa) in U.S. As can be concluded regarding Fig. 1, the yield strength impacts less the carbon emissions than the steel typology, because of major alloying content differences. Indeed, hot-rolled steels are higher embodied CO_2 than cold-rolling steel because of the additional cold

rolling process. The explication for the higher values given for hot-dip galvanizing comes from the chemical compositions, these steels are containing more alloying elements. This feature can be confirmed by examining the GWP of modules A1 to A3 given by EPD from two manufacturers [14], [15] as reported in
Table 1.

Producer	ArcelorMittal [15]	SSAB [14]
Hot dip galvanized steel (Zinc coating): EN10346	2.56	2.42
Hot rolled coils: EN10149-1, EN10025-1 to 4	2.23	2.16
Hollow sections: EN10210 & EN10219	2.27	2.30
Heavy plates: EN10025-1 to 6	2.60	2.71
Structural sections and bars (mix BOF and EAF)	0.84	/



(a) GWP from Ruukki adjusted with data from SSAB EMEA

(b) GWP for SSAB EMEA sheet and strip steel [kg CO_2equ/kg steel]

Fig. 1. GWP evolutions as a function of yield strength according to Steel Eco-Cycle project

Table 1. GWP for modules A1 to A3 depending on the steel typology and the steel producer

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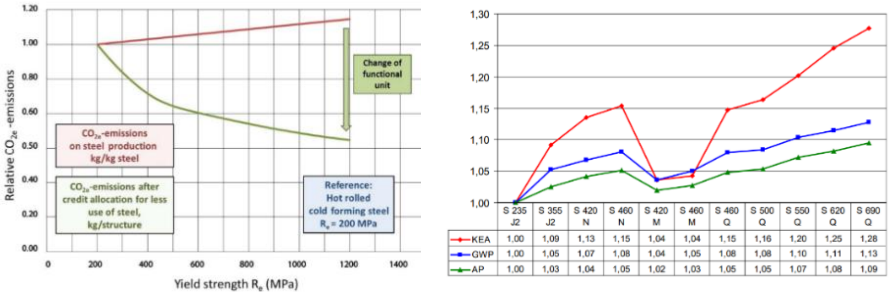
2.2 Evolution of the relative emissions

Some papers in literature [10], [16], [17] give also the relative GWP of high strength steels as reported in Fig. 2.



(a) The steel Eco-cycle for cold-forming steel[10]

(b) Stroetmann, 2011 for heavy plates [16], [17]

Fig. 2. Relative GWP of high strength steels according to the scientific literature

As can be seen in Fig. 2, the relative CO_2 equivalent emissions seem to be included between 1.0 and 1.15. In other words, passing from a regular to a high strength steel grade represents a carbon emission increase of less than 15%. The increase is even less when considering S355J2 as reference instead of S235J2. The weight saving must be sufficient to counterbalance this increase and to present an environmental benefit in considering high strength steels.

In conclusion of the literature review, it seems that the yield strength only slightly affects the carbon emissions, it is even sometimes neglectable regarding the relative GWP. However, in order to validate these observations, relative GWP of high strength steels are evaluated in this study based on their chemical compositions.

3. RELATIVE CARBON EMISSIONS OF HSS BASED ON STEEL ALLOYING ELEMENTS

According to Steel Eco-Cycle project [10], alloys have a major effect on the environmental impact value of steels especially for a given production process. Indeed, greenhouse gas for carbon steel (cradle-to-gate) are cumulative and can be divided as:

$$GWP = GWP_{steelworks,\ site\ specific} + GWP_{Rolling\ \&\ coating,\ site\ specific} + GWP_{steelworks,\ upstream} + GWP_{Rolling\ \&\ coating,\ upstream} + GWP_{alloys,\ upstream} \quad (1)$$

Upstream emissions correspond to emissions taking place before raw materials enter in the steel production mill (production of raw materials, transport, …). To produce higher yield strength, more alloying elements are added to reach a higher material resistance which can probably have a big impact on the total emissions of this grade. Some examples are given in the handbook for scientists and researchers, it is besides clearly indicated that the alloy production in the total environmental impact is higher for a metal coated steel than for a classical hot-rolled steel due to the alloy content differences. To perform some investigations considering the impact of alloys on total environmental impact, database and literature papers have been consulted to get some values for the hardening alloying element production as reported in **Table 2**.

Table 2. Greenhouse gas emissions of alloying elements according to [18]-[20]

Alloying elements	Fe	C	FeMn	FeSi	FeV	Ti	FeNi	FeMo	B
GWP	1.5	3.66	1.5	11.345	87.492	15.297	9.355	11.7	1.5
Source	EI 2.2	CO_2=3.66*C content	IPCC 2006	Gabi 2021.1	Gabi 2021.1	Gabi 2021.1	Gabi 2021.1	EI 2.2	EI 2.2

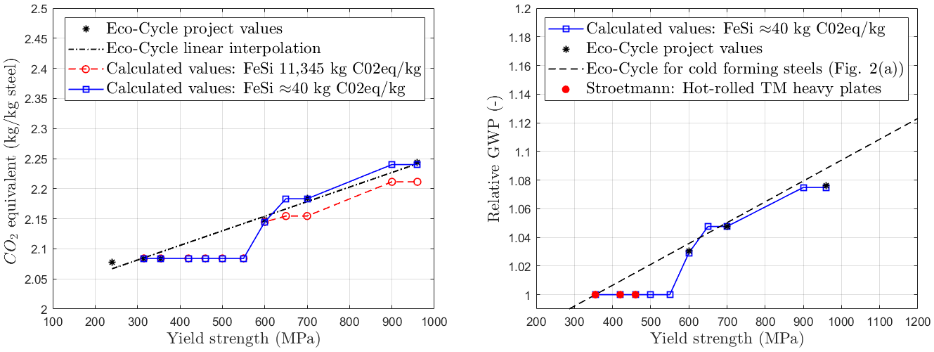
The pursued methodology consists in evaluating, for a given steel category, the relative GWP of high strength steels based on their chemical compositions. The upper threshold of the alloy percentages will be considered given these maximum values are provided in product standards (EN10149-2 for thermo-mechanically rolled steel for cold forming [21], EN10025-2 for as rolled [22], EN10025-3 for normalized [23], EN10025-4 for thermo-mechanically rolled [24] and EN10025-6 for quenched and tempered steels [25]). This approach is conservative as it will a bit overestimate the relative GWP of high strength steels. The GWP of a given steel grade could therefore be conservatively computed as:

$$GWP_{grade} = GWP_{reference} + \sum_{i=1}^{n} \Delta_{alloy_i} * GWP_{alloy_i} \quad (2)$$

Where, $GWP_{reference}$ is the reference global warming potential for a given section typology, n is the number of alloying elements present in the steel chemical compositions of this steel category, Δ_{alloy_i} is the difference between the percentage of the steel alloy i for the studied grade and the reference steel and GWP_{alloy_i} is the unitary GWP for the alloy i production according to **Table 2**.

3.1 Validation of the methodology based on steels from EN10149-2

The methodology has been validated on existing values in the scientific literature for thermomechanically hot-rolled coils for cold-forming according to the chemical compositions prescribed in the corresponding product standard EN10149-2 [21]. The results are represented in Fig. 3.



(a) CO_2 equivalent comparison based on alloy contents in EN10149-2

(b) Relative CO_2 values with S355MC as reference

Fig. 3. Validation of the methodology for thermomechanically hot-rolled coils for cold-forming according to EN10149-2

The developed methodology enables to realise that the linear interpolation performed in the scientific literature was not realistic as the chemical composition remains unchanged up to S550MC, only the Manganese (Mn) content changes to reach higher yield strengths. Then, Titanium (Ti), Molybdenum (Mo) and Boron (B) must be added to the chemical compositions to reach higher yield strengths, this explains the origin of the step in the evolution between S550MC and S600MC. The first computation gave a good correspondence with literature emissions up to this step, then there is a small gap. As can be seen in Fig. 3(a), this small gap comes from the Ferrosilicon (FeSi) production emission factor which seems to be a bit underestimated in Table 2.

3.2 Relative emissions for steels according to EN10025-2 & EN10025-4

According to the values of Stroetmann (Fig. 2b), even for heavy plates, the relative GWP remains constant for yield strengths up to 460-500MPa whatever the steel quality. Therefore, the developed methodology has also been applied for as-rolled steel (EN10025-2) and thermomechanically hot-rolled steels (EN10025-4) to see if similar conclusions can be highlighted for other steel qualities. The reference emission for S355 is taken equal to 1.13 kg Co_2 eq/ton according to a Bauforumstahl EPD for sections and heavy plates [9], this EPD is seen as a reference in Europe for structural steel products. The production shares in this EPD are 26% Basic Oxygen Furnace route (primary steel production) and 74% Electric Arc Furnace route (secondary steel production) which are a realistic current market shares for steel sections according to the World Steel Association [4]. All results are shown in

As a conclusion, the relative GWP is equal to 1.0 until S500M-S550M for products covered in EN10149-2 and EN10025-2 because their chemical compositions do not change significantly until S500. Only the manganese content changes but the increase is counterbalanced by the iron reduction because their unitary emissions are identical (**Table 2**). Nonetheless, for EN10025-4, Vanadium (V), Nickel (Ni), Molybdenum (Mo) and Silicon (Si) contents increase with yield strength, what has an impact on the relative emissions as represented in **Errore. L'autoriferimento non è valido per un segnalibro.**. However, the methodology is a rough estimation with upper percentages as given in the corresponding standards, so the relative emissions are probably lower. In addition, this steel category from EN10025-4 (thermomechanically hot-rolled) presents some other advantages such as; the microstructure advantage in terms of fine grain structure which leads to a reduction of the crack risk after welding (good cold formability and toughness) and the low carbon equivalent values. Based on this low carbon equivalent, the preheating before welding can usually be avoided which lead to substantial time, additional cost, and environmental savings.

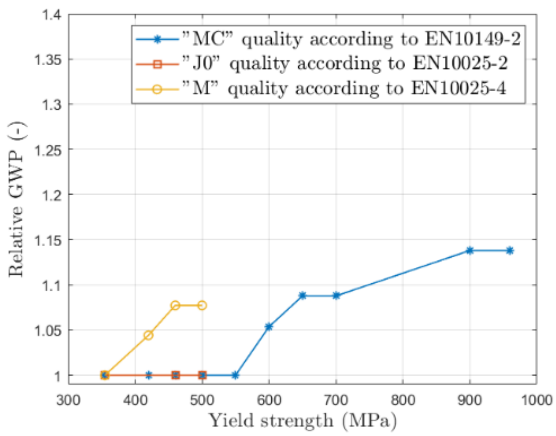


Fig. 4 for each steel qualities.

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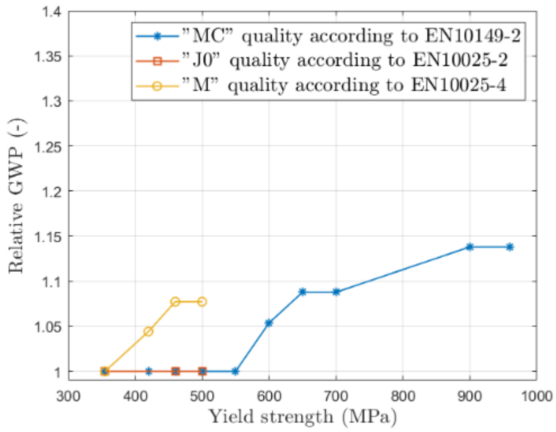


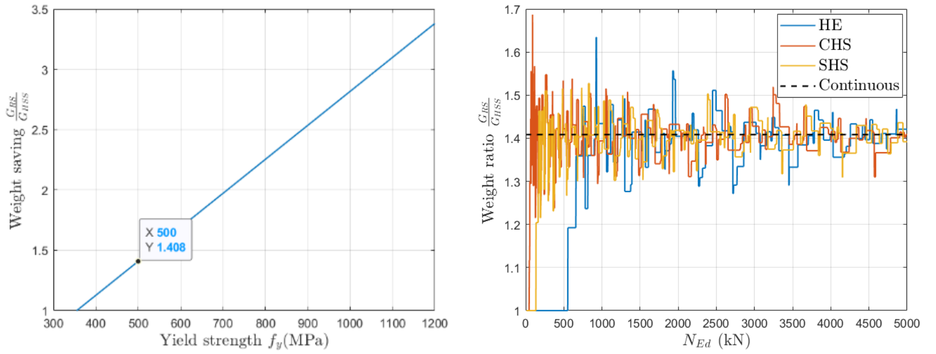
Fig. 4. Evolution of GWP as function of yield strength depending on the steel quality

4. EVALUATION OF THE ENVIRONMENTAL BENEFIT IN USING HSS

As high strength steels are stronger than conventional mild steel, they lead to a consistent material reduction while maintaining the same resistance. These weight savings often counterbalance the CO_2 emission increases especially for tension members for which the material resistance governs the ULS design. In this section, the environmental benefit in using high strength steels will be discussed for several isolated members subjected to various loadings. The mild steel is S355 while the high strength steel considered is S500 herein. The current EN1993-1-1 [26] version covers steel grades up to S460 while the new upcoming version PrEn1993-1-1[27] extends the rules up to S700. The high strength steel grade S500 is currently the highest hot-rolled grade produced for hot rolled sections as reported in European product standards. In addition, this grade is commercialised by ArcelorMittal for hot-rolled sections, besides this grade has entered in their product catalogue in 2019. The weight savings will be described in this section for this special grade, but the methodology may be applied for higher steel grade in a prospective study.

4.1 Tensile members

As already mentioned, for those members, the resistance is directly proportional to the yield strength so the benefit in using high strength steels is expected to be large. This type of structural members is usually found in structural trusses for which elements are mainly subjected to axial forces. Fig. 5 reports weight savings depending on the yield strength (a) and section typology (b). As can be seen in Fig. 5, except for applied loads below the plastic resistance of the first profile in S355, the weight savings are always higher than 1.2. Therefore, according to existing relative carbon emissions for high strength steels, there is always an environmental benefit in using high strength steels for tension members.



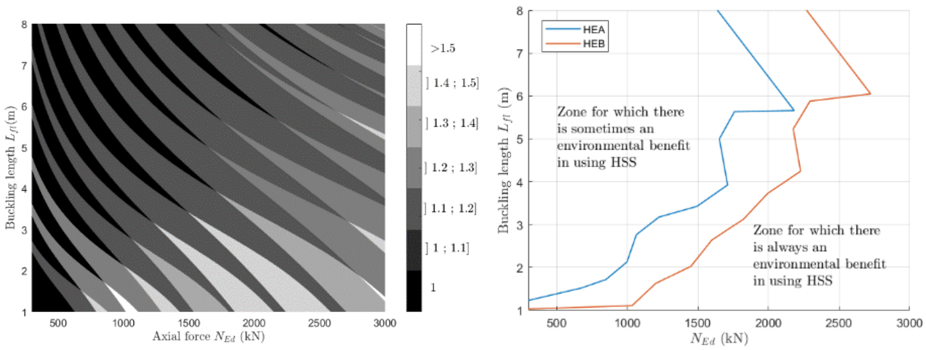
(a) Weight saving in case of a continuous material

(b) Weight saving for standard profile catalogs and for S500

Fig. 5. Weight savings for tension members

4.2 Compression members

For compression members, the resistance capacity depends on the member length as the flexural buckling instability limits the element slenderness. The weight savings resulting by using S500 instead of S355 are reported in Fig. 6.



(a) Weight ratio for HEA compression members (buckling about weak axis)

(b) Limits for the benefit zones depending on the section typology

Fig. 6. Weight savings for compression members

As illustrated in Fig. 6(a), the only zones for which the weight saving is below 1.1 are areas where the optimum profile is the same whatever the grade designed. Accordingly, a limit line can be plotted for each section typology to separate the zone for which there is always an environmental benefit and the zone for which there is sometimes an environmental benefit as shown in Fig. 6(b).

5. CONCLUSIONS

Via steel chemistry and process conditions, steel producers can increase the yield strength to produce the so-called high strength steel grades. The weight savings generated using high strength steel led to cost and environmental burden reductions. Indeed, for a given load bearing capacity, high

strength steels enable to use less resources than with conventional steel grades. From the design stage, we must think to use materials more efficiently in a life cycle approach, using the right material in the right place, and exploiting efficiently the material mechanical properties.
This paper illustrates that the percentage of carbon emission reductions can be estimated as equal to the percentage of weight savings because the increase in the relative carbon emissions resulting in using a higher yield strength is not significant up to S550 for several steel qualities. This conclusion has been achieved through a developed methodology consisting in evaluating the steel carbon footprint based on the steel alloying contents. In addition, weight savings have been evaluated for tension and compression members, these comparisons have highlighted huge zones of environmental benefit in using high strength steel grades.
As a perspective, the methodology is thought to be applicable to other product standard such as for the American product standards including ASTM A913, ASTM A709 that already cover steel grades up to 80 ksi (550MPa). The exercise could be performed to generalize the conclusion of these preliminary investigations. Eventually, the environmental benefit in using high strength steels could be realised for elements subjected to other loading conditions.

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KEYWORDS

High Strength Steels, Sustainability, Environmental aspects, Global Warming Potential (GWP), Structure optimization