

A literature review on the structural behavior of high strength steel columns

Uma revisão de literatura acerca do comportamento estrutural de pilares de aço de alta resistência

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Abstract

Steel is an essential material for engineering due to its properties, such as strength, and durability. High strength steels (HSS) have the potential to enhance these qualities, particularly in the construction of taller, lighter, and more slender structures. However, there remains a knowledge gap regarding the structural behavior of these materials. In this context, the present study aims to evaluate, through a Systematic Literature Review (SLR), the methods employed by researchers to determine the structural behavior of high strength steel columns subjected to compression and flexural compression in both principal axes of inertia. Research findings have highlighted significant limitations in the current design methods for high-strength steels, which were originally developed for conventional materials. Specifically, factors such as steel type, cross-sectional dimensions, residual stresses, and initial geometric imperfections have proven to be critical in determining structural performance. It was observed that applying existing design methods may result in overly conservative solutions or, in some cases, fail to adequately account for the behavior of high-strength steels in structural calculations and verifications.

Keywords: High strength steel. Structural analysis. Flexo-compressed columns. Design methods.

Resumo

O aço é um material essencial para a engenharia em virtude de suas propriedades, tais como resistência e durabilidade. Os aços de alta resistência (HSS) podem potencializar tais qualidades, sobretudo na obtenção de estruturas mais altas, leves e esbeltas. Entretanto, ainda existe uma lacuna de conhecimento acerca do comportamento estrutural desses materiais. Neste sentido, o presente trabalho tem por objetivo avaliar, por meio de uma Revisão Sistemática de Literatura (SREE) os métodos empregados por autores na determinação do comportamento estrutural de pilares de alta resistência, submetidos à compressão/flexocompressão em ambos os eixos de inércia. As pesquisas destacaram limitações significativas nos métodos de projeto vigentes para aços de alta resistência, que foram originalmente desenvolvidos para materiais convencionais. Em particular, fatores como o tipo de aço, as dimensões da seção transversal, as tensões residuais e as imperfeições geométricas iniciais mostraram-se determinantes no desempenho estrutural. Observou-se que a aplicação dos métodos de projeto existentes pode levar a soluções excessivamente conservadoras ou, em alguns casos, à inadequação para abranger completamente o comportamento dos aços de alta resistência nos cálculos e verificações estruturais.

Palavras-chave: Aços de alta resistência. Pilares flexo-comprimidos. Análise estrutural. Métodos de dimensionamento.

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Introduction

The emergence of modern technologies has enabled the development of more efficient, safe, sustainable, and economically attractive construction materials. In the case of structural steels, the main properties targeted for material improvement are mechanical and corrosion resistance, ductility, and stiffness, progressively achieving lighter and more slender structures.

Ma, Li and Chung (2018) state that high strength steels (HSS) refer to those materials with a yield strength equal to or greater than 460 MPa, which is two to three times higher than conventional steel. Shi, Ban, and Bijlaard (2012) further refined this classification by categorizing steels into high-strength and ultra-high-strength types. Ultra-high-strength steels (UHSS) are defined as those with a yield strength equal to or greater than 690 MPa, while steels with lower yield strengths are classified as high-strength.

Such advanced strength steels allow not only the creation of lighter and more slender structures but also less complex structures in terms of the number of elements and connections. Material savings in a structure built with high-strength steels can reach up to 20% compared to conventional steel consumption (Pan, 2018). Currently, gas emissions and energy consumption are the main environmental concerns in steel production. The application of high strength steels reduces material consumption as well as carbon dioxide emissions in the steel and construction industries (Nidheesh; Kumar, 2019).

However, for the full utilization of these materials in civil construction, it is important to study and understand its composition, its physical-chemical properties, and especially its mechanical behavior when subjected to significant loads. Some technical standards have been updated to include strength classes above 460 MPa, such as the European standard Eurocode 3, EN 1993-1-1 (ECS, 2005), which provides a design method for steel elements with classes up to 460 MPa, and Eurocode 3, which establishes supplementary rules for designs with steels up to 700 MPa. The Brazilian standard NBR 8800 (ABNT, 2024) covers structural steels with yield strength classes up to 450 MPa, with high-strength steels not fully encompassed by its calculations and verifications.

Recently, several international studies have been developed to analyze the behavior of HSS structures, among which the most relevant are the studies conducted by Ban *et al.* (2012), Wang, Li and Chen (2012), Ban *et al.* (2013), Ma *et al.* (2017), Ma, Li, and Chung (2018), Li *et al.* (2020), Su *et al.* (2021a, 2021b, 2021c), Li *et al.* (2022), Zhou *et al.* (2023), Ferreira Filho *et al.* (2024), Su *et al.* (2024), Yin and Yang (2024), and Zhu, Yun and Gardner (2024). In all these works is identified the study of factors influencing the resistance of high strength steel columns, such as residual stresses and initial geometric imperfections, as well as the adherence of existing international design criteria to the behavior of these steels. However, according to Ban *et al.* (2013), further research is necessary on the behavior of HSS structural elements.

This work aims to evaluate, through a Systematic Literature Review (SREE), the methods employed by authors in determining the structural behavior of HSS columns when subjected to compression and flexo-compression around the axes of greater and lesser inertia. The study identifies the key parameters influencing the load-bearing capacity of these elements and assesses the alignment of existing standards with the experimental and numerical results reported in the literature.

Theoretical framework

To obtain technical input and theoretical references related to the theme of this research, a structured bibliographic survey was conducted, encompassing relevant studies on the behavior of HSS columns. In this process, the SREE (Azevedo *et al.*, 2022) methodology was used as the literature review method. This is an adaptation of the ProKnow-C (*Knowledge Development Process - Constructivist method*) proposed by Ensslin *et al.* (2010), considering its relevance in the academic field, as indicated in their studies Carvalho *et al.* (2020), Ensslin *et al.* (2015, 2018), Kruger *et al.* (2015), Sato *et al.* (2018) and Vieira *et al.* (2019).

The SREE methodology was executed as proposed by Azevedo *et al.* (2022), with its development consisting of two subsequent macro-steps:

- (a) selection of the bibliographic portfolio; and
- (b) bibliographic analysis and systemic analysis.

Methodology

Selection of the bibliographic portfolio

Step 01: keywords search

In the first macro-step developed in the method, the initial parameters of the research are defined. The keywords defined for this work were searched, considering the search filters for titles, abstracts, and keywords of the target works. The final keywords defined were: High Strength Steel, Columns, and Overall buckling. The search consisted of refining the terms to obtain the highest number of relevant works for the theme.

The databases used were Science Direct, Scopus, Compendex, and Web of Science, due to their relevance to the field of Engineering, especially to the subfield of Civil Engineering. All these databases are indexed by the site (Capes, 2016). Regarding the search period, documents published in the last 15 years were considered, given the slow scientific advancement in the field of Civil Engineering. As for the types of documents searched, the search was restricted to articles.

Table 1 illustrates the results obtained from the search in the databases with the refined terms that returned the most articles and were consequently used to conduct the research and compile the portfolio articles (Table 2).

Steps 02 and 03: selection, extraction, and removal of duplicates

Following the methodology proposed by Azevedo *et al.* (2022) the above listed documents were extracted. These were cataloged using Mendeley® software to allow better management and analysis of references. Subsequently, out of the 654 titles found, a cross-check of the articles was conducted to identify and eliminate duplicate works, resulting in 238 remaining works.

Steps 04 to 07: selection of works best aligned with the theme

Afterwards, the works were evaluated by verifying (i) the alignment of the title and abstract with the research theme, as well as (ii) scientific recognition (related to the number of times the work is cited by others). Thus, the selection of relevant articles, candidates for composing the bibliographic portfolio, was conducted.

Analyzing the articles found and their bibliographic references, six more articles with strong adherence to the theme of this research were identified. These were then inserted into the analysis flow of candidate articles for the literature review. After reading the title, abstract, and keywords, fifty-three works were selected for full reading. Out of this amount, thirty-two were selected to compose the bibliographic portfolio, given their alignment with the research theme. The portfolio is shown in Table 2.

The bibliometric analysis was carried out considering: (i) the scientific recognition of the articles through the number of citations on Google Scholar and (ii) the JCR (Journal Citation Reports) impact factor according to the Clarivate Analytics™ database in 2022 (most recent classification), in which articles with a score greater than 3,130 points are considered well ranked. Figure 1 illustrates the scientific impact of the articles, measured by the number of citations. The data reveals a clear trend: older publications tend to accumulate more citations over time. Notably, the three most-cited articles in the portfolio were authored by Ban *et al.* (2012), Shi, Ban and Bijlaard (2012), and Ban and Shi (2018).

Furthermore, analyzing the Figure 2, it is inferred that the quality of the journal has a greater influence on the scientific recognition of the article, since journals with a higher impact factor, that is, better classified, usually have greater visibility in the scientific community and tend to pre-sent robust theoretical, numerical, and/or experimental studies.

Table 1 - Number of articles by keyword combination in the databases

Key words	Bases	Results
“High Strength Steel” AND “Columns” AND “Overall buckling”	Science Direct	142
	Scopus	240
	Compendex	138
	Web of Science	134
	Total	654

Table 2 - Portfolio of selected articles

Nº	Authors	Steel Class fy (MPa)	Year	Nº of reports	Vehicle Report
1	Ban <i>et al.</i> (2012)	Q460	2012	221	Journal of Constructional Steel Research
2	Shi, Ban and Bijlaard (2012)	Q690, Q960	2012	163	Journal of constructional steel research
3	Wang, Li and Chen (2012)	Q460	2012	11	Journal of Constructional Steel Research
4	Shi, Hu and Shi (2014)	Various	2014	124	International Journal of Steel Structures
5	Li <i>et al.</i> (2016a)	Q690	2016	104	Journal of Constructional Steel Research
6	Li <i>et al.</i> (2016b)	Q690	2016	47	Journal of Constructional Steel Research
7	Ban and Shi (2018)	Various	2017	151	Structures and Buildings
8	Ma <i>et al.</i> (2017)	Q690	2017	60	Journal of Constructional Steel Research
9	Ma, Li and Chung (2018)	Q690	2018	32	Journal of Constructional Steel Research
10	Jiang <i>et al.</i> (2019)	Q690	2019	20	Engineering Structures
11	Sun, Liang and Zhao (2019)	Q690	2019	92	Journal of Constructional Steel Research
12	Li <i>et al.</i> (2020)	Q960	2020	28	Journal of Constructional Steel Research
13	Cao <i>et al.</i> (2021)	Q800	2021	18	Thin-Walled Structures
14	Su <i>et al.</i> (2021a)	Q960	2021	49	Thin-Walled Structures
15	Su <i>et al.</i> (2021b)	Q960	2021	57	Thin-Walled Structures
16	Su <i>et al.</i> (2021c)	Q960	2021	57	Thin-Walled Structures
17	Sun <i>et al.</i> (2021)	Q690	2021	23	Thin-Walled Structures
18	Wang <i>et al.</i> (2021b)	Q420, Q960	2021	22	Engineering Structures
19	Ferreira Filho <i>et al.</i> (2022a)	Various	2022	16	Engineering Structures
20	Ferreira Filho <i>et al.</i> (2022b)	Various	2022	0	ce/papers
21	Gao <i>et al.</i> (2022)	Q700	2022	3	Journal of Constructional Steel Research
22	Li <i>et al.</i> (2022)	Q800	2022	10	Thin-Walled Structures
23	Liu, Chen and Chan (2022)	Q690, Q460	2022	20	Thin-Walled Structures
24	Qiao, Li and Mou (2022)	Q770	2022	4	Thin-Walled Structures
25	Su <i>et al.</i> (2022)	Q960	2022	25	Thin-Walled Structures
26	Su and Zhao (2022)	Q960	2022	28	Thin-Walled Structures
27	Chen, Liu and Chan (2023)	Various	2023	18	Engineering Structures
28	Ferreira Filho <i>et al.</i> (2023)	Q690	2023	0	ce/papers
29	Ferreira Filho <i>et al.</i> (2024)	Q690	2024	3	Journal of Constructional Steel Research
30	Su <i>et al.</i> (2024)	Q960	2024	14	Engineering Structures
31	Yin and Yang (2024)	Q1100	2024	0	Thin-Walled Structures
32	Zhu, Yun and Gardner (2024)	Various	2024	4	Thin-Walled Structures

Figure 1 - Scientific recognition of the articles

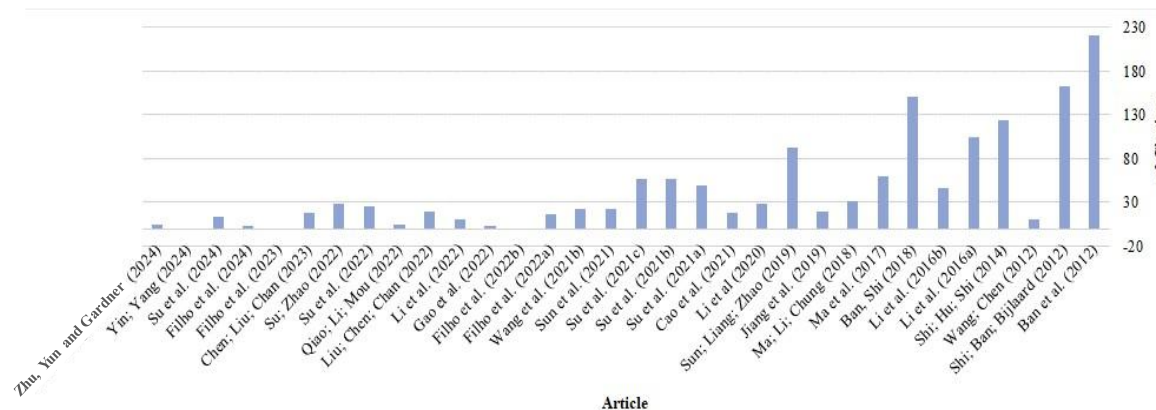
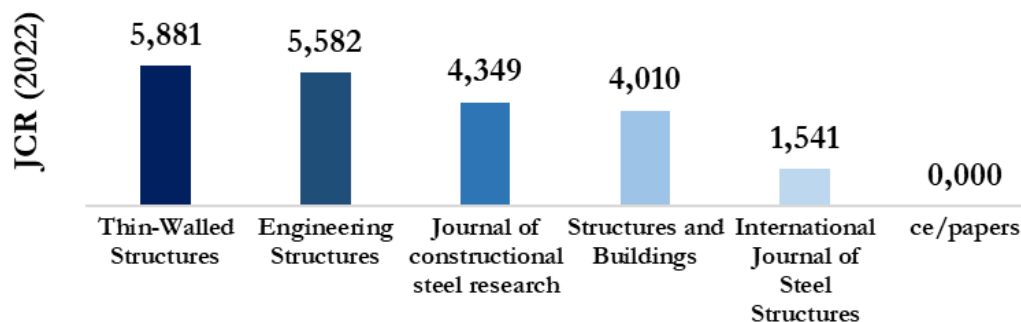


Figure 2 - JCR classification of journals



Among the selected portfolio components, the journals *Thin-Walled Structures* (JCR = 5,881), *Engineering Structures* (JCR = 5,582), and *Journal of Building Structures* (JCR = 5,582) are the most relevant, presenting good scientific recognition by the evaluating entities. For the journal *Ce/Papers*, no evaluation references were found. Although the *Ce/Papers* database includes conference papers, it was still considered relevant due to the significance of the articles on the topic. Furthermore, as highlighted by the journal's website, all articles undergo a peer review process.

Out of the thirty-two selected articles, six present experimental research, specifically Li *et al.* (2016a), Ma *et al.* (2017), Li *et al.* (2020), Wang *et al.* (2021b), Quiao Li and Mou (2022), and Chen, Liu and Chan (2023). Another six studies are essentially numerical: Li *et al.* (2016b), Ma, Li and Chung (2018), Jiang *et al.* (2019) and Ferreira Filho *et al.* (2022b, 2023, 2024), which are compared to experimental results from other bibliographies and/or results obtained by direct calculations of methodologies determined by standards, leading to accurate comparisons that highlight the best results obtained.

Additionally, eighteen articles present both experimental and parametric studies: Ban *et al.* (2012), Shi, Ban and Bijlaard (2012), Wang, Li and Chen (2012), Sun, Liang and Zhao (2019), Cao *et al.* (2021), Su *et al.* (2021a, 2021b, 2021c, 2022, 2024), Sun *et al.* (2021), Gao *et al.* (2022), Li *et al.* (2022), Liu, Chen and Chan (2022), Ferreira Filho *et al.* (2022a), Su and Zhao (2022), Yin and Yang (2024) and Zhu, Yun and Gardner (2024). Finally, the remaining two articles are literature reviews: Shi, Hu and Shi (2014) and Ban and Shi (2018), which also use appropriate comparison methods.

This analysis revealed that scientific works need to improve their methodological quality, presenting more comprehensive studies with statistical data treatment to achieve better results in comparison with similar works available in the literature.

Step 08: bibliographic and systemic analysis

The next step involves the analysis of each article in the bibliographic portfolio, aiming to identify research gaps regarding the behavior of HSS H-section columns, as well as determining which existing standards and their specificities best reflect the behavior of these elements in structural design. Different observation prisms were considered, namely:

- behavior of HSS H-section columns subjected to axial compressive force and combined axial compression and bending moments based on experimental, numerical, and normative analyses;
- factors influencing the behavior of HSS columns; and
- criteria of current standards for the design of HSS columns.

The lens addresses the behavior of welded H-section steel columns with varying cross-sectional dimensions and effective length, subjected to isolated and combined compression and bending loads. The following sections present the results achieved and discussions from the perspective of each research lens.

Results and discussions

Behavior of HSS H-section columns subjected to axial compressive force and combined axial compression and bending moments

Table 3 presents, in a summarized manner, the main characteristics of the HSS elements used in the selected bibliographic portfolio, including the types of cross-sections, the yield strength of the steel (f_y), and the

bending axes evaluated, as well as the essential parameters that influence the behavior of the columns, such as residual stresses (RS), initial geometric imperfections (IGI), and local buckling (LB).

Table 3 - Characteristics of the elements and analysis parameters used

Nº	Authors	Section type	Steel Classfy (MPa)	Axis	Load type	RS	IGI	LB	Type of study
1	Ban <i>et al.</i> (2012)	Box, I	Q460	Major/Minor	Compression	✓	✓	✓	Experimental/ Numerical
2	Shi, Ban and Bijlaard (2012)	I	Q690, Q960	Major/Minor	Compression	✗	✓	✓	Experimental/ Numerical
3	Wang, Li and Chen (2012)	I	Q460	Major/Minor	Compression	✓	✓	✗	Experimental/ Numerical
4	Shi, Hu and Shi (2014)	Box, I	Various	-	Compression	✓	✓	✓	Literature review
5	Li <i>et al.</i> (2016a)	Box, H	Q690	Major/Minor	Compression	✗	✓	✓	Experimental
6	Li <i>et al.</i> (2016b)	Box, H	Q690	Major/Minor	Compression	✓	✓	✓	Numerical
7	Ban and Shi (2018)	Box, I	Various	-	Compression	✓	✗	✓	Literature review
8	Ma <i>et al.</i> (2017)	H	Q690	Major/Minor	Flexo-compression	✓	✓	✓	Experimental
9	Ma, Li and Chung (2018)	H	Q690	Major/Minor	Flexo-compression	✓	✗	✓	Experimental/ Numerical
10	Jiang <i>et al.</i> (2019)	H	Q690	Minor	Flexion	✓	✓	✓	Experimental
11	Sun, Liang and Zhao (2019)	I	Q690	Minor	Compression	✓	✓	✓	Experimental/ Numerical
12	Li <i>et al.</i> (2020)	Box, I	Q960	-	Compression	✓	✗	✗	Experimental
13	Cao <i>et al.</i> (2021)	H	Q800	Minor	Compression	✓	✓	✓	Numerical
14	Su <i>et al.</i> (2021a)	I	Q960	Minor	Compression	✓	✓	✓	Numerical
15	Su <i>et al.</i> (2021b)	I	Q960	Minor	Compression	✓	✓	✓	Experimental/ Numerical
16	Su <i>et al.</i> (2021c)	I	Q960	Minor	Flexo-compression	✓	✓	✓	Experimental/ Numerical
17	Sun <i>et al.</i> (2021)	I	Q690	Minor	Flexo-compression	✓	✓	✓	Experimental/ Numerical
18	Wang <i>et al.</i> (2021b)	H	Q420, Q960	Major/Minor	Compression	✓	✗	✓	Experimental
19	Ferreira Filho <i>et al.</i> (2022a)	I	Various	Major/Minor	Compression	✓	✓	✓	Experimental/ Numerical
20	Ferreira Filho <i>et al.</i> (2022b)	I	Various	Major/Minor	Compression	✓	✓	✓	Numerical
21	Gao <i>et al.</i> (2022)	Box	Q700	Major/Minor	Compression	✓	✓	✓	Literature review
22	Li <i>et al.</i> (2022)	Box	Q800	Major/Minor	Compression	✓	✓	✓	Experimental
23	Liu, Chen and Chan (2022)	T	Q690, Q460	Major/Minor	Compression	✓	✓	✓	Experimental/ Numerical
24	Qiao, Li and Mou (2022)	H	Q770	Major/Minor	Compression	✓	✓	✓	Experimental
25	Su <i>et al.</i> (2022)	I	Q960	Minor	Compression	✓	✓	✓	Experimental/ Numerical
26	Su and Zhao (2022)	I	Q960	Minor	Flexo-compression	✓	✓	✓	Experimental/ Numerical
27	Chen, Liu and Chan (2023)	I	Various	-	Compression	✓	✓	✓	Experimental
28	Ferreira Filho <i>et al.</i> (2023)	I	Q690	-	Compression	✓	✓	✗	Numerical
29	Ferreira Filho <i>et al.</i> (2024)	I	Q690	Major/Minor	Compression	✓	✓	✓	Numerical
30	Su <i>et al.</i> (2024)	I	Q960	Major/Minor	Flexo-compression	✓	✓	✓	Numerical
31	Yin and Yang (2024)	I	Q1100	Minor	Compression	✓	✓	✓	Experimental/ Numerical
32	Zhu, Yun and Gardner (2024)	I	Various	Major/Minor	Compression	✓	✓	✗	Experimental/ Numerical

In this context, the results from the studies by Ban *et al.* (2012), Shi, Ban and Bijlaard (2012), Shi, Hu and Shi (2014), Li *et al.* (2016 a, 2016b), Ma *et al.* (2017), Ma and Chung (2018), Jiang *et al.* (2019), Sun, Liang and Zhao (2019), Li *et al.* (2020), Sun *et al.* (2021), Ferreira Filho *et al.* (2022a, 2022b, 2023, 2024), Gao *et al.* (2022), Li *et al.* (2022), Liu, Chen and Chan (2022), Su *et al.* (2021a, 2021b, 2021c, 2022, 2024), Yin and Yang (2024), and Zhu, Yun and Gardner (2024) contributed significantly to the evaluation of the adequacy of normative prescriptions for the design of columns made with high strength steel.

Regarding the standards, Table 4 synthesizes, stratified by author, which standards were considered adequate for the design of HSS columns, and which were deemed inadequate and/or insufficient. This is because, according to the authors, the standards used in their studies were not suitable for the design of the analyzed structures due to a range of factors. These factors include the buckling curve underestimating or overestimating the global buckling resistance of columns, or the inadequacy of other calculation parameters considered, such as those associated with initial geometric imperfections and residual stresses.

Table 4 - Qualitative analysis of the adherence of standards to the design of HSS columns according to the evaluated articles

Article	AISC 360	EURO CODE 3	GB 50017	AS 4100	AIJ 2002
	American	European	Chinese	Australian	Japanese
Ban <i>et al.</i> (2012)	✓	✓	✓	N/A	N/A
Shi, Ban and Bijlaard (2012)	✓	✓	✓	N/A	N/A
Shi, Hu and Shi (2014)	X	X	X	N/A	N/A
Li <i>et al.</i> (2016a)	✓	X	✓	N/A	N/A
Li <i>et al.</i> (2016b)	✓	✓	✓	N/A	N/A
Ma <i>et al.</i> (2017)	X	✓	X	N/A	N/A
Ma, Li and Chung (2018)	✓	✓	✓	N/A	N/A
Sun, Liang and Zhao (2019)	✓	✓	N/A	✓	N/A
Jiang <i>et al.</i> (2019)	✓	✓	✓	N/A	N/A
Su <i>et al.</i> (2021a)	X	X	✓	N/A	N/A
Su <i>et al.</i> (2021b)	✓	✓	✓	N/A	N/A
Su <i>et al.</i> (2021c)	X	N/A	N/A	X	N/A
Sun <i>et al.</i> (2021)	X	✓	N/A	N/A	N/A
Cao <i>et al.</i> (2021)	X	X	N/A	N/A	N/A
Qiao, Li and Mou (2022)	X	X	X	N/A	✓
Liu, Chen and Chan (2022)	✓	✓	N/A	✓	N/A
Su and Zhao (2022)	✓	X	N/A	N/A	N/A
Li <i>et al.</i> (2022)	X	X	X	N/A	N/A
Gao <i>et al.</i> (2022)	✓	X	X	N/A	N/A
Su <i>et al.</i> (2022)	X	X	N/A	X	N/A
Ferreira Filho <i>et al.</i> (2024)	N/A	X	N/A	N/A	N/A
Su <i>et al.</i> (2024)	X	✓	N/A	N/A	N/A
Yin and Yang (2024)	✓	✓	N/A	✓	N/A
Ferreira Filho <i>et al.</i> (2023)	N/A	X	N/A	N/A	N/A
Zhu, Yun and Gardner (2024)	✓	✓	N/A	N/A	N/A
N° citations	23	24	13	5	1
✓	13	13	8	3	1
	57%	54%	62%	60%	100%
X	10	11	5	2	0
	43%	46%	38%	40%	0%

From Table 4 and Figure 3, it is observed that the most frequently used standard in the studies was the European one, with twenty-four citations, or 75% of the articles in the portfolio. Of these, thirteen considered that the standard could be used for the design of HSS structures, achieving a 54% approval rate relative to the total citations in articles. On the other hand, eleven authors found the standard inadequate, resulting in a 46% disapproval rate.

By contrast, the American standard was cited in twenty-three articles, with a 57% approval rate and a 43% disapproval rate. The Chinese standard was cited by thirteen articles, of which eight approved it and five disapproved it, obtaining a 62% approval rate among the articles in which it was cited. The Australian standard was cited by five articles, with three approvals and two disapprovals. Finally, with only one citation each, the Japanese standard received total approval.

When contrasting the approval data of the standards with the classes of steel used, as shown in Figures 4 and 5, it is noted that columns made of steel with a yield strength of 690 MPa (used in 11 studies) were the most compliant with the design standards, especially the European standard (8 approvals and 2 disapprovals), the American standard (8 approvals and 3 disapprovals), and the Chinese standard (5 approvals and 1 disapproval).

Subsequently, steels with a yield strength of 960 MPa, the subject of seven studies, were found compatible with three of the five standards: American (3 approvals and 4 disapprovals), European (1 approval and 5 disapprovals), and Chinese (3 approvals). Steel with a yield strength of 800 MPa, used in two studies, was found incompatible with all the evaluated standards. Other steel classes, 420, 460, 700, and 770 MPa, having been used in only one study each, do not provide a significant basis for evaluation.

Figure 3 - Approval and disapproval counts for structural design standards cited

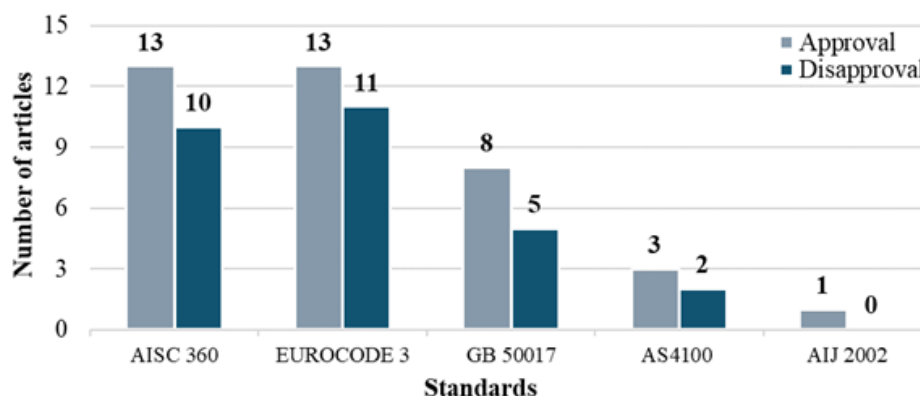


Figure 4 - Compliance of standards correlated to the type of steel analyzed

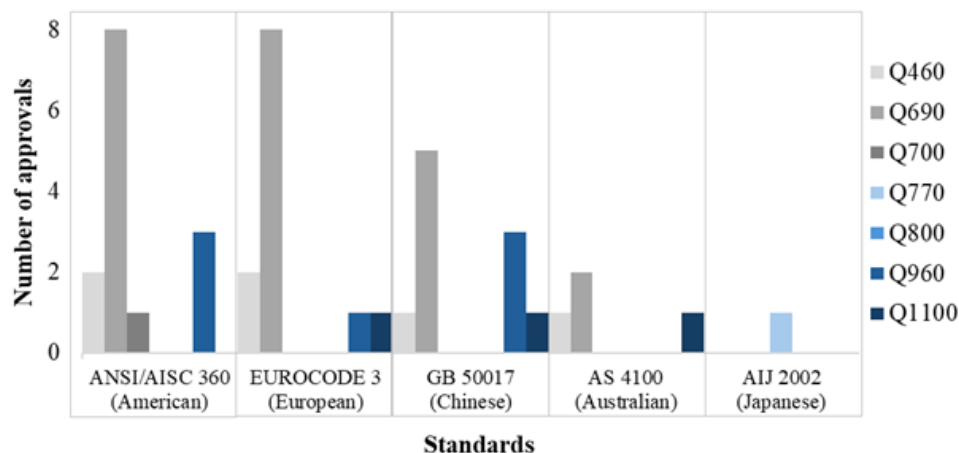
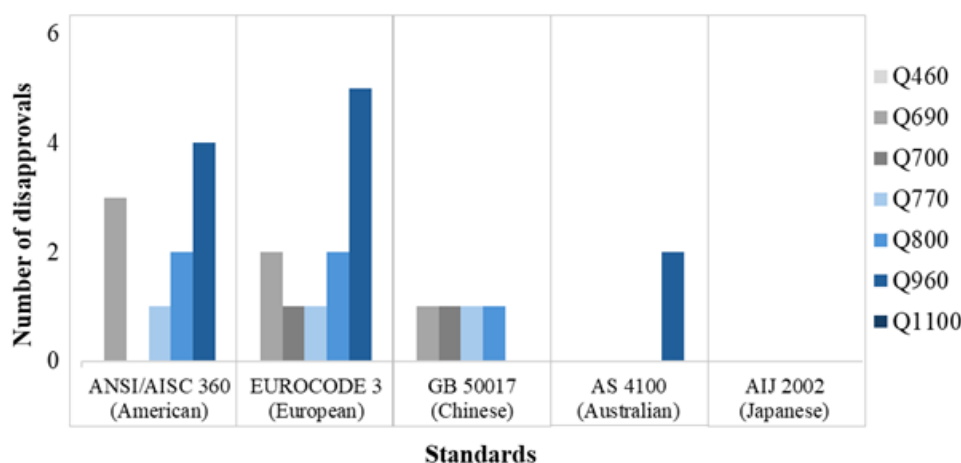


Figure 5 - Non-compliance of standards correlated to the type of steel analyzed



Based on the analyses conducted, it is concluded that there is significant variability in the adoption of existing standards worldwide among the works conducted by the analyzed authors. The most frequently used standards were the Chinese standard GB 50017 (NSPRC, 2017), the European standard Eurocode 3 EN 1993-1-1 (ECS, 2005), and the American standard ANSI/AISC (AISC, 2016), in all its revisions. The Australian standard SAA (1998) was referenced in five studies, while the Japanese standard AIJ (2002) was cited only once.

Factors influencing the behavior of HSS columns

Complementing the previous lens, this research prism evaluates the factors influencing the behavior of H-section HSS columns subjected to compression and flexo-compression, as evidenced by the authors of the studies analyzed in this research. Among the main factors investigated are geometric and material imperfections, which significantly impact the structural responses of loaded structures.

A deeper understanding of these factors, in conjunction with those from Lens 1, allows for a more robust evaluation of the actual behavior of the analyzed material. This, in turn, enables the development and calibration of finite element models that incorporate geometric and material nonlinearities, making it possible to replicate the structural behavior of columns experimentally analyzed by other authors, particularly Ban *et al.* (2012), Ma *et al.* (2017), Ban and Shi (2018), Ma, Li and Chung (2018), Li *et al.* (2020, 2022), Wang *et al.* (2021a, 2021b), Quiao, Li and Mou (2022), Chen, Liu and Chan (2023), Yin and Yang (2024) and Zhu, Yun and Gardner (2024).

Stress-strain behavior

HSS can exhibit different material properties beyond the yield point. Figure 6 shows a comparison of typical stress-strain curves for several types of steel, obtained from tensile tests on specimens, as presented by Ban and Shi (2018). It is noted that, despite having higher yield stresses, HSS exhibit the same modulus of elasticity as common steels. It is also observed that as the yield strength of the steel increases, the yield plateau becomes shorter and typically disappears when the yield strength exceeds 500 MPa (Ban; Shi, 2018, p. 628).

Furthermore, according to the authors, the strain-hardening capacity of the material, represented by the ratio between the ultimate tensile strength and the yield strength (f_u/f_y), the longitudinal strain, and the elongation at rupture decrease with increasing material grade. For all the steels analyzed, the yield strength values obtained from the tests were higher than the nominal values.

Several simplified constitutive models have been suggested in the literature to represent the behavior of HSS in numerical analyses. Some of these models were presented by Ban and Shi (2018) and are shown in Figure 7. The trilinear model (Figure 7b) applies to HSS that exhibit a yield plateau, while the other models (bilinear, nonlinear, and multilinear) shown in Figures 7a, 7c, and 7d are applied to HSS without a yield plateau.

Ma, Li and Chung (2018) used the trilinear model (Figure 7b) for conventional steels with $f_y = 235$ MPa and the bilinear model (Figure 7a) for HSS with $f_y = 690$ MPa to analyze the behavior of columns subjected to

flexo-compression and concluded that strain hardening did not improve the buckling resistance of steel columns.

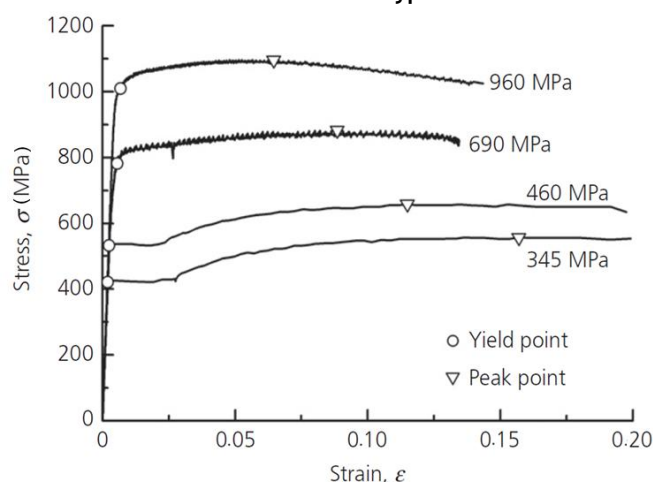
Wang *et al.* (2021b) analyzed welded H-section profiles subjected to compression, composed of plates with yield strengths of 420, 550, 690, and 960 MPa. For each type of steel, two plate thicknesses were considered, 12 and 16 mm. Three tensile test specimens were evaluated for each steel plate. The average values of the tensile test results from the three specimens were considered as the mechanical properties of each steel plate.

Steel plates with $f_y = 690$ MPa and thicknesses of 12 and 16 mm, as well as the plate with $f_y = 960$ MPa and a thickness of 16 mm, exhibited distinct yield plateaus, while the other plates showed a smooth transition from yield stress to tensile stress without a yield plateau. As the steel strength increased, the f_u/f_y ratio decreased.

Steels with yield strengths below 460 MPa and between 500 and 700 MPa met the ductility requirements for structural steel in Eurocode 3. Steel with a yield strength above 700 MPa exhibited low ductility; however, there is no ductility requirement in the specification.

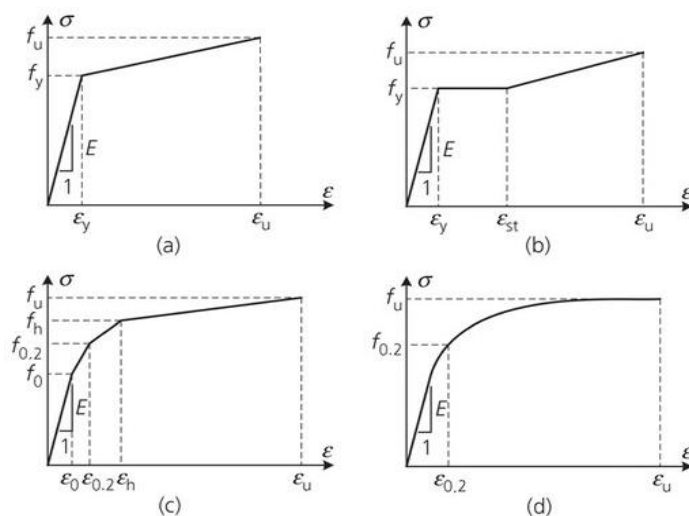
The authors concluded that the axial ductility of the specimens decreased with increasing steel strength and slenderness ratio. For the numerical analysis via Finite Element Method (FEM), the authors adopted the multilinear kinematic hardening model for 460 MPa steels with a yield plateau (Figure 7c) and the trilinear kinematic hardening model for 960 MPa steels (Figure 7b) under the Von Mises yield criterion.

Figure 6 - Comparison of stress-strain curves for various types of steel



Source: adapted from Ban and Shi (2018, p. 628).

Figure 7 - Simplified Stress-Strain Models for Steels: (a) Bilinear; (b) Trilinear; (c) Multilinear; (d) Nonlinear



Source: adapted from Ban and Shi (2018, p. 628).

Additionally, when evaluating other recent works by the authors of the articles that make up the bibliographic portfolio, a study conducted by Leroy Gardner (author of article 32) is found, in which the author analyzes several stress-strain models and establishes a unified numerical formulation, suitable for HSS, to determine the ultimate tensile strength f_u and deformation ε_u as a function of nominal tensile strength f_y (Dissanayake *et al.*, 2025).

The authors state that for hot-rolled steels with $460\text{MPa} \leq f_y \leq 890\text{MPa}$ and carbon content $C \geq 0.2\%$, the shape of the stress-strain curve will exhibit a yield plateau. However, for $C \leq 0.2\%$, no yield plateau will be present. For cold-formed steels, stress-strain responses will be assumed to be similar those of hot-rolled steels. The predictive expressions are given below (Equations 1 to 4):

The ultimate tensile strength f_u may be determined from:

$$f_u/f_y = 1 + (200/f_y)^{1.75}, \text{ for hot-rolled steels} \quad \text{Eq. 1}$$

$$f_u/f_y = 1 + (130/f_y)^{1.40}, \text{ for cold-formed steels} \quad \text{Eq. 2}$$

The ultimate strain ε_u given by:

$$\varepsilon_u = 1 + (f_y/0.0008E)^{-1.55}, \text{ for hot-rolled steels} \quad \text{Eq. 3}$$

$$\varepsilon_u = 1 + (f_y/0.0008E)^{-1.65} \text{ for cold-formed steels} \quad \text{Eq. 4}$$

The strain hardening strain ε_{sh} related the end of the yield plateau can be determined from (Equation 5):

$$\varepsilon_{sh} = 0.1 f_y/f_u - 0.055, \text{ to } 0.015 \leq \varepsilon_{sh} \leq 0.030 \text{ for hot-rolled steels} \quad \text{Eq. 5}$$

Dissanayake *et al.* (2025) mention that these recommended stress-strain models are appropriate for the combination of analytical, numerical and design models for hot-rolled or cold-rolled HSS elements and structures, covering a range of strength classes.

Residual stresses

Residual Stresses (RS) result from the conditions of uneven heating and cooling during the profile manufacturing process. These stresses play a significant role in the design of steel columns as they are the primary cause of nonlinearity in the stress-strain diagram in the inelastic region, significantly affecting the compressive strength of steel members (Viana *et al.*, 2020; Silva *et al.*, 2018).

The value and distribution of residual stresses depend on the geometry of the cross-section, the rolling or welding temperature, the cooling conditions, and the material properties. Research on the effect of these parameters on the distribution of RS has been conducted since the last century. However, the test results for the yield strength of steels greater than 460 MPa are more recent and are considered to correspond to more refined welding procedures and material properties.

Residual stresses and their influence on the structural behavior of HSS have been investigated by Ban *et al.* (2012), Wang, Li and Chen (2012), Ma, Li and Chung (2018), Li *et al.* (2020), and Chen, Liu and Chan (2023), among others, showing that the distribution and magnitude of RS are essential parameters for evaluating the buckling behavior of columns, in the numerical modeling of structural elements, and in the development of accurate design standards, especially when using HSS.

Based on an extensive literature review regarding experimental results and parametric analyses using nonlinear FE models, Ban and Shi (2018) stated that the global buckling resistance in HSS columns is significantly improved compared to conventional steel columns, as the compressive residual stresses in HSS are considerably lower compared to compressive residual stresses in conventional steels.

Figure 8 shows the residual stress distribution models for I-sections formed by plates made from thermal cuts, developed from experimental tests, proposed by Ban *et al.* (2012) and Wang, Li and Chen (2012). In Figure 8, σ_{tf} and σ_{tw} denote the tensile residual stresses and σ_{cf} and σ_{cw} the compressive residual stresses in the flanges and web, respectively, a_f is the width of the tensile region in the flange, and a_w is the width of the tensile region in the web.

It is observed that there is a tensile residual stress σ_f at the edge of the flanges of the profile. According to Ma, Li and Chung (2018), the values of the tensile residual stresses at the edges of the flanges can be conservatively

considered equal to 50 MPa for welded H-sections with yield strengths of up to 800 MPa. As for the stress distribution, similar models were found in the studies of Li *et al.* (2020).

When steel plates are assembled by welding to form the profile, the residual stresses resulting from the welding process are superimposed on the residual stresses from the cutting process. Thus, the residual stress distribution of thermally cut sections differs from the residual stresses of non-thermally cut I-sections. According to Wang *et al.* (2021b), the residual stress distribution in profiles with thermally cut plates can result in a higher ultimate load capacity for welded H-section columns, especially for those under bending around the minor axis.

In addition to residual stress distribution models for specific HSS cross-sections developed from experimental tests, unified models for application in numerical simulations have been proposed in recent literature. Notable examples include the models by Ban *et al.* (2012, 2013) for welded I-sections and box sections based on existing experimental results, including specimens with various cross-sectional dimensions and steel yield strengths.

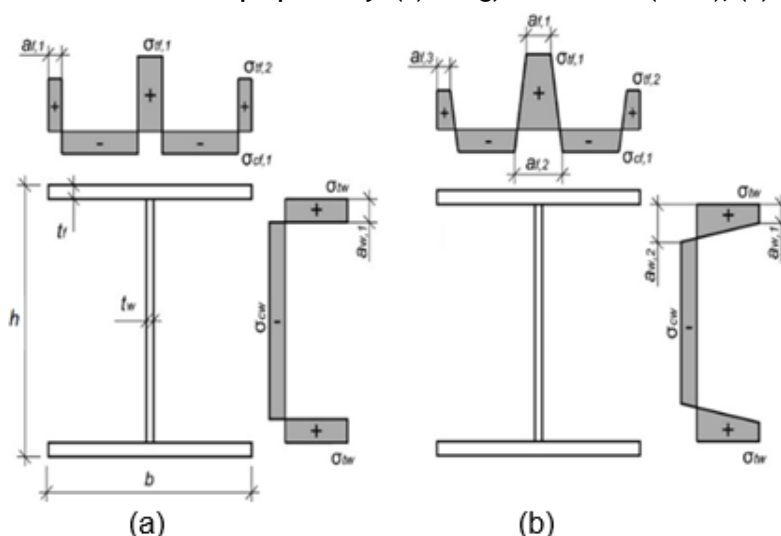
Ban *et al.* (2012, 2013) showed that the wider the steel plates, the larger the areas in compression, and consequently, the lower the compressive residual stresses. The authors also demonstrated that the magnitudes of residual stresses in welded high-strength steel sections are independent of the material's yield strength values, a conclusion previously established in the literature.

Furthermore, Li *et al.* (2020) concluded that residual stresses tend to increase with the increasing width to thickness ratio of the profiles. Based on experimental studies, the authors proposed simplified equations for their prediction, primarily based on the thickness of the plates that make up the profiles. They established that the ratio of residual stresses to the yield strength (σ_{rc}/f_y) can be conservatively limited to 0.3 for design purposes, making it safe to be adopted by engineering practice.

When evaluating other studies about residual stresses in HSS by the authors of the articles that make up the bibliographic portfolio, the work developed by Chung K. (author of article 09) is found, in which he evaluated the effects of welding on 690 MPa and 960 MPa steel sections. The study highlights that the heat generated during the welding process leads to transformations in the material's microstructure and consequent changes in the mechanical properties throughout the section. These changes result in a reduction of mechanical capacities in the heat-affected zones, leading to a strength decrease of approximately 4% in 690 MPa steel sections and 3% in 960 MPa steel sections (Zhu *et al.*, 2025).

However, although the residual stress measurement results of HSS H-sections presented in this SLR showed that residual stress distribution depends on the geometric characteristics of the section and welding parameters, and not on the material itself, more analyses are needed. These analyses should consider the unified models presented in the literature and propose new models to better represent the behavior of steel columns subjected to axial compression and flexo-compression.

Figure 8 - Residual stress distribution proposed by: (a) Wang, Li and Chen (2012); (b) Ban *et al.* (2012)



Source: adapted from Ban *et al.* (2012, p. 146) e Wang, Li and Chen (2012, p. 164).

Initial geometric imperfections

Another important nonlinearity that significantly influences the strength of columns is the initial imperfection of the structural elements. These imperfections appear during the industrial manufacturing process due to the unevenness of the plates and the deformation that occurs during the cutting and welding process, leading to inevitable significant deviations from the ideal straight axis of the bars Wang *et al.* (2021b).

According to Somodi and Kövesdi (2017), the geometric imperfections of HSS columns are smaller compared to conventional steel columns due to better manufacturing control and higher quality. Typically, in theoretical analyses, curvatures are approximated by a sinusoidal shape with the maximum amplitude of the initial imperfection located at the central section of the element.

Studies by Li *et al.* (2016a, 2016b), Ma *et al.* (2017), Ma, Li and Chung (2018), Jiang *et al.* (2019), Sun, Liang and Zhao (2019) and Su *et al.* (2021c) emphasize the importance of integrating initial imperfections and residual stresses into column strength models, which are fundamental for establishing design criteria.

Criteria of current standards for the design of HSS columns

The dispersion of experimental results for the buckling strengths of columns is primarily caused by differences in cross-sectional geometry, steel strength, manufacturing methods, buckling planes, and other factors. These differences are addressed by grouping columns into specific resistance curves. However, there are differences in the grouping criteria and resistance curves between design standards due to varying considerations of initial geometric imperfections, residual stress distribution and amplitudes, the formulation of expressions, and the strategy to achieve the necessary reliability levels.

Ban and Shi (2018) synthesized the main information regarding experimental and numerical results for HSS columns conducted by various authors, aiming to summarize the key conclusions obtained. Regarding the design criteria adopted for H-section columns, the authors suggested that, according to the flexural axis of the column's cross-section (major or minor inertia), specific buckling curves outlined in the European standards EN 1993-1-1 (ECS, 2005) should be adopted, as shown in Table 5.

Shi, Hu and Shi (2014) also selected buckling curves from the European and Chinese standards for HSS, based on experimental results obtained by various authors, including some cited in this work, such as Shi, Ban and Bijlaard (2012) and Ban *et al.* (2012, 2013). Table 6 presents the proposed buckling curves for each steel grade and flexural axis for H-section HSS columns.

The studies conducted by Shi, Hu and Shi (2014) and Ban and Shi (2018), in relation to the European standard, converge for H-section columns made of steel grades 460, 690, and 960 MPa, for the major and minor inertia axes. For other grades, Ban and Shi (2018) recommend using the Chinese standard, particularly indicating the "b" curve of the mentioned standard, but adopting new values for α .

The experimental and numerical test results by Sun *et al.* (2021) and Su *et al.* (2022) were employed to evaluate the applicability of the design interaction curves, as prescribed in EN 1993-1-1 (ECS, 2005) and ANSI/AISC 360 (AISC, 2016), for HSS of 690 MPa and 960 MPa, respectively, for welded I-sections.

Table 5 - Proposed buckling curves of the european standard for HSS columns

fy (MPa)	Proposal curve	
	major axis	minor axis
460	b	b
500	a	b
550	a	b
620	a	b
690	a	a
800	a	a
890	a	a
960	a ₀	a

Source: adapted from Wang, Li and Chen (2012, p. 165).

Table 6 - Proposed buckling curves of the european and chinese standards for HSS columns

fy (MPa)	EN 1993-1-1 (ECS, 2005)		GB 50017 (NSPRC, 2003)	
	major axis	minor axis	major axis	minor axis
460	b	b	b	b
500	-	-	b	b
550	-	-	b	-
620	-	-	a	b
690	a	a	a	b
800	-	-	a	b
890	-	-	a	a
960	a	a	a	a

Source: adapted from Shi, Hu and Shi (2014, p. 880).

The evaluation results by Sun *et al.* (2021) indicated that Eurocode 3 provided accurate, consistent, and safe strength predictions for welded I-sections of 690 MPa steel, of classes 1 and 2, under flexo-compression loading relative to the major and minor inertia axes but underestimated the strength for class 3 welded I-sections. The strengths of 690 MPa welded I-sections under combined loading flexed relative to the major axis were well predicted by ANSI/AISC 360 (AISC, 2016) but were conservative for the minor axis. The linear interaction curves adopted in GB 50017 (NSPRC, 2017) led to the highest level of conservatism for 690 MPa welded I-sections under combined loading.

However, Su *et al.* (2022), based on the results of graphical and quantitative evaluation, concluded that the interaction curves of the three standards provided a conservative design for 960 MPa steels.

When evaluating other studies on the design of HSS structures by the authors of the articles that make up the bibliographic portfolio, the works conducted by Wang Y. (author of articles 3 and 18) and Zhao O. (author of articles 11 and 26) were found, in which, apart from the different cross-sections analyzed by each author, the design standards provided by EC3 and AISC resulted in imprecise and inconsistent strength predictions for Tse, Wang, and Yun (2021). However, for Jiang and Zhao (2023) and Zhang, Zhong, and Zhao (2023), the AISC standard provided consistent predictions, while EC3 yielded more conservative results.

Conclusions

In this study, a Systematic Literature Review (SLR) was conducted to investigate the methods employed by authors to study the behavior of High Strength Steel (HSS) columns subjected to axial and flexural compression, in conjunction with current design standards. The SREE method proved efficient in obtaining technical input, resulting in a portfolio of thirty-two relevant articles fully aligned with the research theme. The analysis led to the following conclusions:

- Key Factors Influencing Behavior:** several factors influence the strength of HSS columns, such as residual stresses and initial geometric imperfections. Analyses of these steels should consider different magnitudes and configurations of these factors to effectively evaluate the behavior of columns under diverse conditions;
- Design Standards and Their Applicability:** the Chinese, European, and American standards were the most frequently used by the authors. For H-section columns made of steel grades Q460, Q690, and Q960, the curves described in the European standard, specifically curves "a" and "b," can be adopted for the major and minor inertia axes. However, for columns made of other steel grades, the correspondence between the curves of the European and Chinese standards should be further evaluated. Despite the relative effectiveness of these standards, significant disagreement exists among researchers regarding the best design approach for HSS columns; and
- Recommendations for Future Research:** there is a pressing need for the development of supplementary rules that prescribe methodologies and calculation criteria for advanced high-strength steels in column design. These rules would ensure greater reliability and safety in structural design, particularly for materials with yield strengths exceeding 460 MPa. This highlights the importance of bridging existing gaps through focused research in several key areas.

Firstly, experimental investigations should be undertaken to complement numerical models, particularly for columns subjected to flexural compression and eccentric loading. These studies would enable the calibration

of unified, parameterized models for residual stresses and geometric imperfections, applicable across various cross-sectional shapes.

Secondly, design standards require substantial improvements to accommodate high-strength steels with yield strengths above 700 MPa. This includes formulating specific buckling curves tailored to different sections and loading conditions. Comparative analyses of international standards are essential to identify best practices and work toward unified safety and reliability criteria for global applications.

In parallel, there is a need to explore new materials, particularly advanced HSS types with unique strain-hardening behavior and high-temperature performance. Furthermore, investigating hybrid steels that combine different strength grades in composite sections could further optimize material performance and structural efficiency.

Lastly, the sustainability and material efficiency of HSS merit attention. Assessing the environmental impact and material savings in large-scale projects is important to highlight HSS's role in reducing CO₂ emissions and promoting sustainable construction practices.

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