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Advancements in Steel as a Material

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ABSTRACT

Structural steel has remained one of the most trusted building material for more than a century. However, owing to its limitations in durability, sustainability, cost-effectiveness (or life-cycle cost) and advancements in the material, it is necessary to explore the materials beyond structural steel. This paper explores the development and experience of three major innovations - weathering steel, stainless steel and high-strenght low-alloy steel. Weathering steel offers superior corrosion resistance in industrial and rural environments through the formation of a protective patina, significantly reducing maintenance costs over its service life. Stainless steel, on the other hand, provides exceptional ductility, aesthetic appeal, and long-term sustainability, despite its higher initial cost. The study also evaluates chemical composition, historical evolution, performance in real-world applications, and suitability for modern civil engineering challenges. By emphasizing life-cycle cost analysis and long-term performance, this paper highlights the practical and environmental benefits of using advanced forms of steel in structural applications.

1.0 Introduction

Structural Steel has been one of the most trusted building materials over the years. The consumption and production are very strong indicators of how an economy is performing. As Barbara et al. summarised, steel plays a critical role in infrastructure development across most countries [1]. This is supported by figures from the World Steel Association, which report a dramatic rise in per capita steel consumption in China—from approximately 170 kg in 2000 to around 628 kg in 2023—closely correlating with the country's rapid economic growth [2].

Since the 19th century, structural steel has gradually replaced older materials like cast and wrought iron. This became possible because by 1856, Bessemer had patented his steel-making process, which marked a breakthrough in the industrial-scale production of steel [3]. Later in 1879, Gilchrist Thomas improved the ductility of steel by overcoming problems associated with using phosphoric iron ores [4]. Continued advancements in the understanding of thermochemical processes further enhanced steel production and solidified its presence across various industries.

Although another modern material, reinforced concrete, gained rapid acceptance post World War 2, the steel demand has consistently gone up [5]. The interest in RCC went up not only owing to conservative industry practices and policies, but also the perception that it provides a better thermal mass. With the rise of composite construction techniques—such as steel-concrete composite sections and decking systems—many of RCC's traditional advantages are now being reconsidered.

Steel, on the other hand, provides significant advantages as a material. Being a homogeneous material with a high strength-to-weight ratio, steel can be prefabricated. There is better quality control as the material is cast in factories (compared to concrete). There is a faster erection and installation, and there is an ease of manoeuvrability [6].

2.0 Limitations of conventional structural steel

One commonly cited drawback of structural steel, particularly when compared to conventional reinforced concrete, is its higher initial construction cost. Steel is often believed to be costly compared to concrete in conventional construction (even though there is a higher scope of optimisation) [7]. This is because of higher labour costs globally. As literature suggests, a more comprehensive life cycle cost (LCC) assessment—rather than focusing solely on upfront expenses—offers a clearer evaluation of steel's true economic viability [8]. Structural steel is also highly sustainable, with over 95% of it being recyclable at the end of its life cycle, reinforcing its long-term environmental and economic benefits [9].

From an architectural perspective, the demand for more versatile and expressive building forms has increased the requirement for high-strength steel capable of accommodating large spans and complex geometries [10]. However, this presents a material trade-off that structural engineers must carefully navigate. Increasing steel strength often involves elevating its carbon content, which inversely affects its ductility, a defining property of structural steel. For optimal balance, the carbon content in structural steel is typically maintained between 0.15% and 0.30%. Below 0.15%, strength becomes insufficient, while above 0.30%, the loss in ductility becomes critical [11].

Another important issue with any construction material is durability over time. For steel, the members are often subjected to rusting and a need for regular painting. Although the cost of maintenance of a steel structure is less than a concrete structure, it is one of the challenges of having a conventional steel structure [8].

Considering these limitations, there is a need to explore some advancements in structural steel as a material.

3.0 Weathering Steel

Weathering steel has proved to be reliable as it forms its own oxide protecting layer known as *Patina* and requires no painting. Due to this self-protecting behaviour, weathering steel structures typically require no painting or rust removal, leading to significant reductions in life-cycle costs [12]. In the United States alone, over 2,000 bridges have been constructed using weathering steel, testifying to its long-term reliability and performance.

3.1 Historical Development

A detailed account of the development of weathering steel had been carried out by Albrecht and Hall [13]. The summary of which is discussed here. The US Steel Corporation, Buck, conducted a large-scale atmospheric exposure test of copper steel in the industrial coke regions (sulphurous fumes) of Pennsylvania, Atlantic City (marine) and Kittanning (rural). This research showed promising results regarding the effect of copper in steels for atmospheric exposure.

Building upon these results, ASTM Committee A-5 initiated a large-scale study in 1916 involving 260 corrugated steel sheets, with copper contents ranging from 0.01% to 0.25%. Testing sites included Fort Pitt (Pittsburgh), Fort Sheridan, and Annapolis. The results demonstrated a significant reduction in corrosion at copper contents as low as 0.04%, closely aligning with Buck's earlier findings of 0.03% [9]. The study was extended by the committee in 1926 at four other locations: Altoona, State College, Sandy Hook and Key West. Larrabee later summarised these findings, highlighting that steels containing a minimum of 0.20 wt% copper exhibited twice the durability compared to steels with only residual copper content [15]. Additionally, it was observed that the presence of phosphorus further improved corrosion resistance.

V.V. Kendall and E.S. Taylerson [13] in 1929 studied the effect of adding phosphorus along with copper further in the sulphurous industrial atmosphere of Pittsburgh. Their work confirmed that the protective influence was stronger in steels than in irons, and although corrosion was less severe in rural environments like Fort Sheridan, the overall trends held across different climates [16]. Following this, the US Steel Corporation launched the first commercial weathering steel, USS Cor-Ten steel. To validate its performance, ASTM and U.S. Steel conducted additional tests during 1941–42. The results confirmed that rust coatings in industrial atmospheres were more protective, with corrosion rates being lower than in marine environments [13].

To test the efficacy of the commercial weathering steel, ASTM Committee A-5 and the US Steel Corporation conducted multiple studies in 1941 and 1942, respectively. They concluded that rust coatings in the industrial atmosphere were more protective, with the corrosion rate dropping to lower values than in the marine atmospheres.

3.2 Chemical Composition

The development of the first WS compositions was initially an empirical task based on steel mass loss results in atmospheric exposure, and not on scientific knowledge of the influence of alloying elements. The early studies of Larrabee and Coburn [3], and later by the ASTM Committee A-5 in 1941 and 1942 by US Steel Corporation, represented an important step forward in the empirical development of WS based on a knowledge of the effect of different alloying elements.

Copper is the most relevant alloying element in the composition of WS. It was the first to be incorporated and led to the birth of weathering steels. Buck [17] revealed that alloying mild steel with copper improved its resistance to atmospheric corrosion; the presence of just 0.04 wt% copper perceptibly improved its anticorrosive behaviour in the atmosphere, and concentrations above 0.25 wt% barely led to any further improvement. Later, in 1962, Larrabee and Coburn confirmed Buck's results, setting a lower limit of 0.05 wt% and an upper limit of 0.20 wt% [3], and noting that the greatest benefit occurred with the first 0.05 wt%.

Phosphorus is not essential for protective patina formation, but its addition to a copper-bearing steel leads to a marked improvement in corrosion resistance. As an alloying element, phosphorus has a notable effect on the mechanical properties of steel and may be beneficial or harmful depending on its content in the alloy and on the processing method. It is estimated that a proportion of more than 0.1 wt% phosphorus can promote brittle fracture in steel when subjected to vibratory forces or blows. its upper limit is controlled by its adverse effect on the mechanical properties of steel, and so phosphorus should not exceed 0.1 wt% in the composition of structural steels intended for atmospheric exposure.

The addition of chromium to mild steel leads to a significant improvement in atmospheric corrosion resistance, though the presence of at least 0.1 wt% Cu is necessary in order for its effect to be more appreciable [Larrabee and Coburn [3]]. However, for copper contents lower than 0.04 wt%, the presence of 0.6–1.3 wt% Cr is slightly detrimental, especially in industrial atmospheres [3], [24]. Although Nickel's presence improves atmospheric corrosion resistance in industrial and marine environments, a higher proportion of nickel is necessary to obtain similar results to copper steels. The beneficial effect of nickel is greatly strengthened by the presence of a small proportion of copper [25]. Thus, 1% Ni together with a small percentage of copper leads to notable improvements in the atmospheric corrosion resistance of WS exposed in marine and industrial environments [3].

The scientific literature has accumulated a great number of studies on the influence of different alloying elements on the corrosion resistance of WS exposed to the atmosphere. However, despite this volume of information, only a relatively small number of relevant scientific conclusions and applications have been drawn regarding the direct effect of alloying elements on the atmospheric corrosion resistance of WS.

3.3 Experience in Use

Weathering steel (WS) has been widely adopted in bridge construction across the United States, with over 1800 bridges employing WS in 43 states and the District of Columbia [17]. Most of these structures have demonstrated satisfactory long-term performance, validating the material's corrosion-resistant properties in appropriate environmental conditions.

However, specific case studies, such as those from the State of Michigan, revealed limitations in performance under certain design and environmental constraints. In bridges with low vertical underclearance (less than 6.1 meters), retaining walls and confined spaces were found to trap salt spray, pollutants, and moisture, especially in areas where expansion joints and seals were compromised [18]. These factors led to accelerated corrosion, particularly on the sheltered bottom flanges, where contaminants such as bird droppings, deicing salts, and debris prevented the formation of a stable, protective patina. In areas with severe corrosion, the steel failed to develop the protective oxide layer that characterizes weathering steel performance [19].

Consequently, in 1980, the Michigan Department of Transportation imposed a statewide ban on unpainted weathering steel for use in highway structures [20]. This action drew national attention and prompted a systematic evaluation of WS bridge performance. Under the coordination of the American Iron and Steel Institute (AISI), a task force comprising experts from steel producers, state highway agencies, and the Federal Highway Administration (FHWA) undertook a comprehensive inspection of 49 WS bridges across Illinois, Maryland, Michigan, New York, North Carolina, Wisconsin, and the New Jersey Turnpike Authority [21]. The findings of this inspection revealed:

1. 30% of the bridges exhibited good performance in all aspects.
2. 58% showed overall satisfactory performance, with only moderate corrosion in specific zones.
3. 12% had generally acceptable performance but with severe localized corrosion [21].

Similar patterns were observed in WS bridges located in Alaska and Iowa, where corrosion on the upper surface of the bottom flanges was frequently reported. These cases typically involved inadequate detailing or poor drainage, which allowed water and pollutants to accumulate on critical surfaces. The report also presents the experience of using WS in Ohio, Texas, California and Louisiana.

On the other hand, many states continued to endorse WS due to its reduced maintenance painting costs. For example, Vermont recommends using WS for bridges. , while states like Illinois, Missouri, and Wisconsin apply it selectively, often limiting use to stream crossings or remote-grade separations for aesthetic or pragmatic reasons [22].

Following this review, 31 states and the District of Columbia foresee using WS, 2 states are hesitant ,and 10 have stopped using it. Indiana, Iowa and Michigan have official policies banning its use. Alaska discontinued the use because of the high cost of steel and a generally humid environment along its southeastern coast. The long life of painting systems in the dry climates of Montana makes painted steel construction more economical than bare weathering steel construction.

Apart from the US, weathering steel (WS) has found notable use in Europe, but it comes with caveats. For example, France cautions the bridge owner and directs them to take all necessary precautions for the use of WS [24]. The Federal Republic of Germany presents an even more conservative approach. Due to observed inconsistencies in the corrosion performance of WS in highway bridges—attributable to microclimatic and detailing factors—the use of WS is restricted and only allowed with special approval from the Department of Transportation (decreasing its adaptability) [25].

3.4 Overview

As on the experience in the US and Europe, conventional weathering steel bridges are in good and satisfactory conditions in most places. There are instances of localised and accelerated corrosion attack, but it has since proven that WS can provide a satisfactory service life with limited maintenance [21], [22], [25].

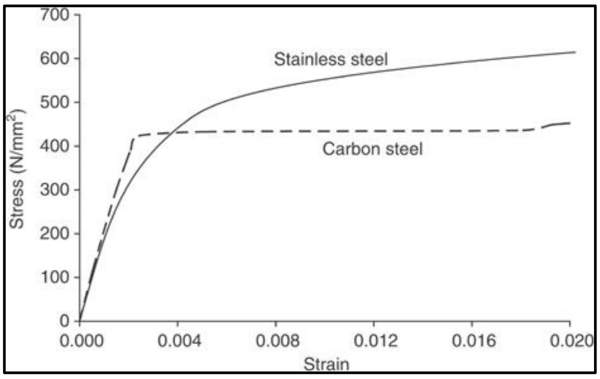
It has also been observed that weathering steel provides better resistance in industrial polluted environments than in marine environments. This involves advancing weathering steel from the perspective of the corrosive products formed. This involves delving deeper into the aspects of atmospheric and marine pollutants. An aspect of cutting the rust formation time can also be explored [26].

The National Highway Research and Technology (NHPRT) Committee has also emphasized the need for developing efficient maintenance methodologies, especially for cleaning and painting of corroded WS bridges that have suffered salt contamination [28].

4.0 Stainless Steel

Stainless steel has traditionally been considered a costly solution to the civil engineering problems - corrosion, strength, ductility, etc. Hence, the use of stainless steel as a primary structural member is limited.Nevertheless, stainless steel offers distinct advantages, not only in terms of corrosion resistance, but also in its mechanical performance, making it a high-performance construction material [28].

Compared to traditional alloy steels, stainless steels are chemically complex. What should interest the Civil Engineer is its differed stress strain behaviour.



Indicative carbon steel and stainless steel behaviour [29]

Unlike carbon steel, which typically shows a well-defined yield point, a yield plateau, and a region of strain hardening, Stainless steel—particularly austenitic grades—displays a rounded stress–strain curve with no distinct yield point, followed by significant strain hardening and enhanced ductility [29], [30].

Since there is no clear yield point, design codes often specify the 0.2% proof stress (stress at 0.2% plastic strain) as a conservative substitute for yield strength. From a ductility perspective, austenitic stainless steels exhibit elongation at fracture between 40–60%, significantly higher than the 20–30% typically observed in carbon steels [29].

4.1 Historical Development

The discovery of stainless steel in the early 20th century was a major advancement in metallurgical engineering, addressing the long-standing problem of corrosion in structural and industrial applications. The first modern stainless steel was developed in 1913 by Harry Brearley in Sheffield, England, during his work on improving rifle barrels. He discovered that a steel alloy containing approximately 12.8% chromium exhibited exceptional resistance to rust when exposed to corrosive environments [31]. This resistance was due to the formation of a passive chromium oxide layer on the surface, which prevented further oxidation. Brearley's work laid the foundation for what would later become known as martensitic stainless steel. In the years following this discovery, other alloy families, such as ferritic and austenitic stainless steels, were developed [32].

A significant milestone in stainless steel development occurred in the 1920s when researchers at Avesta Ironworks in Sweden (now part of Outokumpu) developed austenitic stainless steel with approximately 18% chromium and 8% nickel. This composition became the widely used Type 304 stainless steel, known for its excellent formability and weldability, and continues to serve as the basis for many modern stainless steel grades [33]. Today, the development of duplex, precipitation-hardening, and super-austenitic stainless steels continues to expand the boundaries of stainless steel applications [34].

4.2 Chemical Composition

Stainless Steel is comprised of two words - "Stainless" and "Steel". "Steel" stands for the use of Iron in bulk. The "stainless" part comes from the inclusion of chromium in the alloy. This chromium forms a passive, self-healing oxide layer on the surface that significantly enhances corrosion resistance. For environments with more aggressive exposure conditions, higher chromium content or additional alloying elements may be necessary to ensure long-term durability [35].

The Fe-Cr is at the base of stainless steel, however, it is not limited ot that. There are a host of other elements that are added to enhance its properties. For example, Molybdenum is added to enhance resistance against pitting and Nickel is added to obtain austenite, for instance. Other elements like sulphur, phosphorus and copper may also be added [36], [37].

Stainless steels are commonly classified into six major families based on their microstructure and composition: (1) ferritic, (2) austenitic, (3) martensitic, (4) duplex (austenitic–ferritic), (5) precipitation-hardening, and (6) Mn–N substituted austenitic stainless steels [38], [39]. Austenitic stainless steels typically contain 17–18% chromium and 8–11% nickel, offer very good corrosion resistance and have an austenitic microstructure.

Duplex stainless steels typically contain 22–23% chromium and 4–5% nickel and have a mixed austenitic–ferritic microstructure. The duplex stainless steels offer higher strength, wear resistance and generally corrosion resistance than the austenitics, but at a greater expense.

The commonly available grades for these are EN 1.4301 (austenitic), EN 1.4401 (austenitic) and EN 1.4401 (duplex). The equivalent designations for AISI systems are AISI 304, 316 and 2205, respectively [40].

4.3 Experience in Use

The importance and applications of stainless steel are vast. They are used for low-end applications like utensils, furniture, to most sophisticated instruments that can be used in space vehicles. Applications of stainless steel are omnipresent around us. Iconic structures like the cladding of the Chrysler Building in New York (completed in 1930) and the Gateway Arch in St. Louis (completed in 1965) exemplify early architectural applications of stainless steel [41], [42]. More contemporary and somewhat less prominent examples, which emphasise the recent increased use of stainless steel for its desirable durability and structural properties rather than simply its aesthetics, include buildings, towers, domes, footbridges and road bridges [43].

The Cala Galdana Bridge in Menorca was the first stainless steel road bridge in Europe. The entire process, from the closing of the previous bridge on the same spot to the new bridge opening, took 9 months, leading to minimal disruption in the high tourist season [44]. Another landmark is the Helix Bridge in Marina Bay, Singapore, a 280m long pedestrian bridge. The bridge is the world's first double-helix pedestrian bridge: two helices, built from stainless steel pipes. It is estimated that a conventional box girder ridge would have used five times the weight of steel [45].

Despite being advocated as ideal for corrosion resistance, stainless steel is susceptible to pitting corrosion. This localised dissolution of an oxide-covered metal in specific aggressive environments is one of the most common and catastrophic causes of failure of metallic structures [46].

4.4 Overview

Despite the high initial costs, stainless steel becomes a much viable option considering its advantages of limited maintenance and almost no corrosion. However, beyond this, stainless steel is preferred because it is aesthetic, durable, ductile and sustainable [47].

Historically, the aesthetics of stainless steel have been an important factor in its specification for structural applications. Its appeal is principally due to the surface finish and its ability to retain its appearance without deterioration over time. Stainless steels, particularly the austenitic grades, offer very high ductility and impact resistance. The material is therefore particularly suited to applications where ductility and impact resistance are important, such as offshore structures, crash barriers and structures susceptible to blast loading [48], and has already been applied to railway carriage construction [49].

The construction industry is a major producer of waste material and a major consumer of void (landfill) space [50]. Increasing emphasis is now being placed on the minimisation of construction waste. Stainless steel possesses a combination of high residual value (due to the alloy content) and excellent durability, lending itself to widespread re-use and recycling, bringing practical, financial and environmental advantages.

Cost comparisons made based on the initial material expense of structural components do not reflect the true cost implications of a chosen structural material. A more appropriate analysis would include the additional immediate costs, such as corrosion protection and fire protection, and the longer-term costs associated with maintenance and decommissioning. In such a scenario, stainless steel provides a good option [51].

5.0 Concluding remarks

Steel continues to be a foundational material in civil engineering due to its strength, ductility, and adaptability. Beyond the chemical composition and historical performance, several key factors must be considered when selecting a specific steel grade for a structural application. These include:

1. **Location:** The geographic location of the structure—encompassing climate, humidity, exposure to pollutants, and proximity to marine or industrial zones—plays a critical role in determining corrosion risk. For example, weathering steel performs well in rural and industrial settings but may not be ideal in chloride-rich coastal areas. In contrast, stainless steel demonstrates excellent resilience in both industrial and marine environments, albeit at a higher cost.
2. **Life-Cycle Cost Analysis:** While initial material costs often dominate decision-making, a more comprehensive view considers the entire lifespan of the structure. This includes expenses associated with corrosion protection, maintenance, inspection cycles, and end-of-life dismantling. In many cases, the higher upfront investment in advanced steels is offset by reduced maintenance costs and extended service life, making them economically viable over the long term.
3. **Sustainability:** The environmental impact of construction materials is under increasing scrutiny. Both weathering and stainless steels support circular economy principles. Weathering steel minimizes the need for coatings and paints, reducing environmental contaminants, while stainless steel offers high recyclability and retains its properties even after multiple use cycles, supporting low-waste construction practices.

Ultimately, the type of steel should be selected based on a balanced evaluation of performance requirements, environmental conditions, and long-term value. The growing use of "secondary" or specialized steels such as weathering and stainless steels highlights their significance in modern infrastructure.

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