Design of stainless steel bridges

Stainless steels are inherently corrosion resistant. In the presence of oxygen, a tightly adherent protective layer of chromium oxide spontaneously forms on their surface, which means they can perform satisfactorily in a wide range of environments without protective coatings. This intrinsic characteristic of stainless steel is particularly important for bridges, which often need a long service life with minimum maintenance in aggressive environments.

There is a wide range of stainless steels with varying levels of corrosion resistance and strength. Duplex stainless steels are the most widely used stainless steels for structural components in bridges due to their superior strength and excellent corrosion resistance, while austenitic stainless steels are mainly used for non-structural components. As the level of corrosion resistance of a given stainless steel alloy depends predominantly on its constituent elements, selecting the most appropriate alloy for a particular service environment requires care.

Figure 1 shows one of the Garrison Crossing bridges in Toronto. Duplex stainless steel grade 1.4462 was used to construct the two tied arch bridges spanning 52 m and 44.5 m over two railway corridors. The girders act compositely with the concrete decks.

Fig 1 Garrison Crossing Pedestrian and Cycle Bridges, Toronto, Canada (Photo: Pedelta)

Material properties

Mechanical properties

The stress-strain behaviour of stainless steel is characterised by a gradual yielding with no well-defined yield plateau, and significant strain hardening. For this reason, the yield strength is conventionally defined at the 0.2% offset permanent strain. Duplex stainless steels have similar ductility to carbon steel, whereas austenitic stainless steels are twice as ductile. Table 1 compares minimum specified mechanical properties for both duplex and austenitic stainless steels against those of carbon steel.

Table 1: Minimum specified mechanical properties of stainless and carbon steel plate

Alloy	Modulus of elasticity E (MPa)	Yield strength f_y (MPa)	Ult. tens. strength f_u (MPa)	Elong. (%)
Duplex (1.4462)	200000	460	700	20
Austenitic (1.4401)	200000	220	550	40
Carbon steel (S355)	210000	355	490	22

Austenitic stainless steels do not exhibit a ductile to brittle transition; their toughness slightly reduces with decreasing temperature. Although duplex stainless steels exhibit a ductile to brittle transition like carbon steels, they have adequate toughness for most low temperature applications, e.g. a lean duplex (i.e. less highly-alloyed) typically shows an average toughness of 40 J in base and weld metal at –40°C for up to 30 mm thick material. The more highly-alloyed duplexes show even better toughness.

Stainless steels can absorb considerable impact at high speeds without fracturing due to their excellent ductility (especially the austenitic grades) and their strain hardening characteristics.

Thermal properties

The thermal conductivity of austenitic and duplex stainless steel is about 30% of that of carbon steel. While the coefficient of thermal expansion of duplex grades is similar to that of carbon steel, for austenitic grades it is about 30% higher (see Table 2). As a result, where austenitic stainless steel is used in combination with duplex or carbon steel, the effect of the difference in thermal expansion must be considered in design. Moreover, the high thermal expansion of austenitic grades combined with their relatively low thermal conductivity may lead to greater welding distortions.

Table 2: Thermal properties of stainless and carbon steel

Alloy	Thermal conductivity (W/mK)	Thermal expansion (10^{-6}/°C for T≤100°C)
Duplex	15.0	13.0
Austenitic	15.0	16.0
Carbon steel	53.0	12.0

Design

Grade selection

One of the main reasons for selecting a stainless steel is to take advantage of its corrosion resistance properties, which ensure long-term durability and minimal maintenance.

Within the austenitic and duplex family of stainless steels, there is a wide range of corrosion resistance. The stainless steel Eurocode, EN 1993-1-4 [1] introduces a simple grade selection procedure to guide the designer to an alloy with adequate corrosion resistance for the service environment. (It does not cover situations where the stainless steel is immersed or exposed to chemicals as part of a process flowstream.) Firstly, the service environment is characterised by a Corrosion Resistance Factor (CRF), based on considerations such as the risk of exposure to chlorides from salt water or de-icing salts and exposure to washing by rain. From the CRF, the required Corrosion Resistance Class (CRC) is then determined. Grades are grouped in one of the five CRCs based on their corrosion resistance. Lean duplexes 1.4662, 1.4362, 1.4062, and 1.4162 are in CRC 3 and standard duplex 1.4462 is in CRC 4. More highly-alloyed super duplexes are in CRC 5. Further guidance is given in the Design Manual for Structural Stainless Steel [2].

Member design

Although the structural performance of stainless steel is very similar to carbon steel, its non-linear stress strain characteristics mean that different design rules are needed for stainless steel members. The nonlinearity primarily affects the local and global buckling response, while strain hardening affects the yielding response. Although stainless steel members are likely to exhibit larger deformations compared to carbon steel, the deflection in a duplex stainless steel beam would only be a few percent greater than that of an equivalent carbon steel beam.

Connection design

In general, the same rules for carbon steel bolted connections can be adopted for austenitic and duplex stainless steel bolts, though different provisions for bearing are required to prevent excessive deformation. The corrosion resistance of the bolts should be equivalent to, or better than, the corrosion resistance of the parent metal, i.e. at least austenitic A4 bolts should be used for connecting lean duplex plate, and duplex D4 bolts for connecting standard duplex plate. When bolting stainless steel to carbon steel, bimetallic corrosion should be prevented by isolating the stainless steel electrically from the carbon steel. For example, insulating washers and bushes on both sides of the joint or protective coatings applied to the carbon steel components effectively separates the two metals.

The preload losses due to creep and stress relaxation in stainless steel preloaded bolted assemblies are not significantly higher than those for equivalent connections made of carbon steel. Design rules for preloaded connections have been developed, with slip factors for different stainless steel surfaces and recommendations for bolt tightening [3]. The design rules will be included in the next revision to EN 1993-1-4 and are expected to be included into the execution specification EN 1090-2 [4]. Insulating washers are not appropriate for use in preloaded connections.

Carbon steel design rules for welded connections generally can be applied to stainless steel. A compatible consumable should be selected to ensure the corrosion resistance of the weld metal is at least as good as that of the material being welded. When welding stainless steel to carbon steel, the filler metal should be over-alloyed to avoid cracking. To prevent bimetallic corrosion, the painted coating on the carbon steel should be extended over the weld and onto the stainless steel for a distance of at least 75 mm.

Fatigue

Fatigue behaviour of welded joints mostly depends on the weld geometry rather than the type of steel. The design rules for carbon steel can be safely adopted for austenitic and duplex stainless steel.

Case study 1: Cala Galdana Bridge

This bridge was constructed in Menorca, Spain, and was the first stainless steel road bridge in Europe. The bridge has a span of 55 m and a width of 13 m (Figure 2).

Fig 2 Cala Galdana Bridge, Menorca, Spain
(Photo: Pedelta)

A highly durable material was required for the bridge to achieve a long life with low maintenance requirements. Duplex grade 1.4462 was therefore selected for the main structure of the bridge, with the added benefit of its high strength.

The main structure consists of two parallel arches, two longitudinal beams, and transverse beams (spaced at 2 m) working compositely with a reinforced concrete deck. The arches have a triangular cross-section with a constant depth of 700 mm, while the longitudinal and transverse beams were made of rectangular hollow sections with dimensions of 500x1000 mm for the former and up to 250x570 mm for the latter. All cross-sections were welded from plates with thicknesses ranging from 10 mm to 25 mm [5]. The balustrades were also made from grade 1.4462 duplex stainless steel, while austenitic stainless steel grade 1.4404 was used for the tubular barrier between vehicle and pedestrian areas of the deck.

The bridge was installed in 2005 and inspected after 10 years' service. The duplex 1.4462 stainless steel was in good condition with no corrosion.

Fabrication

The structural components of stainless steel bridges are typically fabricated from plate welded into I-sections, while non-structural elements are usually made from cold-formed sheets or hollow sections. Plate can be procured directly from the stainless steel producer, in project-specific sizes that minimise wastage.

Stainless steel is not a difficult material to work with, although it differs from carbon steel in some respects and should be treated accordingly. Many fabrication and joining processes are similar to those used for carbon steel, but the different characteristics of stainless steel require special attention in a number of areas [6],[7]. It is important that effective communication is established between the designer and fabricator early in the project to ensure that appropriate fabrication practices are adopted. Where possible, it is preferable to use a fabricator with a proven track record of working with structural stainless steel.

The same mechanical fabrication techniques typically used for bending, straightening, or cutting carbon steel plate or sheet can also be used for stainless steels. However, power requirements are greater than those for similar thicknesses of carbon steel due to the higher work hardening rate of stainless steels, and the higher strength of duplex stainless steels. Also, when bending or straightening stainless steel due allowance should be made for spring-back deformations.

Austenitic stainless steels are generally readily welded using common processes. Heat input should be minimised to reduce welding distortion which is generally greater in austenitic stainless steel than in carbon steel. Duplex stainless steels may be less prone to distortion but require control of the minimum and maximum heat input during welding. Austenitic and duplex stainless steels are not normally preheated but special care must be taken to restore the full corrosion resistance of the welded zone, for example by post-weld acid cleaning.

All fabrication processes should be carried out in a clean environment, with tools dedicated exclusively to stainless steel to avoid contamination by carbon steel and iron which increases the potential for surface corrosion. If there is a risk of residual contamination when fabrication is complete, the structure could be sprayed with an acid formulation, and then rinsed. Greater care is also required in storing and handling stainless steel to avoid damaging the surface finish.

Case study 2: Replacement Pooley Bridge

The UK's first stainless steel road bridge was installed in 2020 at Pooley Bridge in the Lake District UNESCO World Heritage Site. It replaces the stone bridge that had been swept away in a storm five years earlier. Duplex stainless steel grade 1.4162 was chosen for the main structure and handrails.

The new bridge is a 40 m span open-spandrel arch bridge, carrying a single-lane road and two pavements, of width varying between 7.5 m and 9.5 m. Welded shear studs enable the 15 mm thick stainless steel plate to act compositely with the concrete deck, hence minimising the overall deck thickness. The single span avoids the need for piers in the river, thereby reducing the flood risk and making the structure more flood resilient.

The high strength of duplex stainless steel helped to minimise the overall weight of the bridge. The entire structure (80 tonnes stainless steel, 220 tonnes concrete) was lifted into place in a single lift with minimum disruption. The bridge has a matt finish, achieved by grinding the welds flat, then sand blasting the entire surface to achieve a uniform appearance.

Fig 3 Replacement Pooley Bridge
(Photo: Outokumpu)

Life cycle cost (LCC) and sustainability

The initial raw material cost of stainless steel is considerably higher than that of carbon steel. However, there are initial cost savings associated with eliminating corrosion resistant coatings. Moreover, the superior strength of duplex grades over conventional carbon steel leads to weight savings, which offsets to some degree the higher material cost and improves constructability.

Eliminating the need for coating maintenance or component replacement due to corrosion leads to long-term maintenance cost savings that can far exceed the initial cost difference. This is particularly important for railway bridges, or bridges over busy traffic areas or water, where access to maintenance is limited or where the cost associated with the temporary closure of the bridge is high. Indirect benefits of reduced maintenance for road bridges include less traffic disruption and a reduction in the greenhouse gas particulate emissions associated with standing traffic.

Stainless steel is 100% recyclable and can be indefinitely recycled into new high-quality stainless steel. 80 to 90% of stainless steel is captured at end-of-life for use in new stainless or carbon steel. The typical recycled content for all types of stainless steel is at least 60%.

Product, design and fabrication standards

In Europe, the design of stainless steel structures is covered by Eurocode 3: Part 1.4 [1]. This standard has a 'supplementary' status, which means it only gives expressions where the carbon steel rules are unsuitable. Therefore it must be used alongside other Parts of Eurocode 3, including EN 1993-2 [8], which covers rules for steel bridges.

The main product standard for stainless steel in Europe is EN 10088, of which Part 4 and Part 5 [9] specify the chemical composition and technical requirements of the different stainless steel grades that are used in structural applications. Part 4 deals with flat products, and Part 5 deals with long products. EN ISO 3506-1 covers austenitic and duplex stainless steel bolts [10], which are available in a range of property classes from 50 to 100 (corresponding to 10% of the ultimate tensile strength of the bolt in MPa).

The European standard that covers the fabrication and erection of cold-formed and hot-finished structural stainless steel products is EN 1090-2 [4], which specifies the requirements for the execution of steel structures to ensure adequate levels of mechanical resistance and stability, serviceability, and durability.

Case study 3: Söderström Rail Bridges

These four rail bridges in Stockholm were built originally in 1957, with a welded carbon steel superstructure. The bridges are 192 m long and heavily used, carrying an average of one train every three minutes. Replacement of the extensively corroded carbon steel members started in 2017, with lean duplex grade 1.4662 chosen for the new bridges.

An LCC study showed that despite the cost of a duplex stainless steel replacement being twice the cost of one in carbon steel (4 M euros compared to 2 M euros), the initial investment was justified because the maintenance costs for the carbon steel structure over the 120 year of service life are considerably higher than the differential in the initial construction cost, leading to savings of tens of millions of euros. The cost of re-painting was particularly high because it requires extensive closures of the busy railway lines, with personnel working on an electrified railway over water [11].

Fig 4 Söderström Rail Bridges being fabricated in lengths of 16-23 m
(Photo: Lars Hamrebjörk)

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