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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 S32205 was used to construct the two tied arch bridges, each spanning about 160 ft (50 m) over two railway corridors. The bridge 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 specified minimum mechanical properties for both duplex and austenitic stainless steels against those of carbon steel.

Table 1: Specified minimum mechanical properties of stainless and carbon steel plate

Alloy	Mod. of elasticity E ksi (MPa)	Yield strength f_y ksi (MPa)	Ult. tens. strength f_u ksi (MPa)	Elong. (%)
Duplex (S32205)	29 000 (200 000)	65 (450)	95 (655)	25
Austenitic (S31600)	28 000 (193 000)	30 (205)	75 (515)	40
Carbon steel (Grade 50)	29 000 (200 000)	50 (345)	65 (450)	21

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 30 ft-lb (40 J) in base and weld metal at –58°F (-50 °C) for up to 1.2 in. (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 alloys) and their strain hardening characteristics.

Thermal properties

The thermal conductivity of austenitic and duplex stainless steel is about 25% of that of carbon steel. While the coefficient of thermal expansion of duplex alloys is similar to that of carbon steel, for austenitic alloys 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 alloys 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 at: 68 °F (BTU/(hr-ft-°F)) 20 °C (W/(m-K))	Thermal expansion between: 68 and 212 °F (10^{-6}/°F) 20 and 100 °C (10^{-6}/°C)
Duplex	8.2 (14.1)	7.4 (13)
Austenitic	8.2 (14.1)	9.1 (16)
Carbon steel	35.0 (60.5)	6.5 (12)

Design

Alloy 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. In order to select an appropriate alloy for the application, it is necessary to characterize the service environment to determine issues like the risk of exposure to chlorides from salt water or deicing salts. The Commentary to the new US stainless steel design specification, ANSI/AISC 370-21 [1], gives guidance on this. AISC Design Guide 27 *Structural Stainless Steel* [2] which serves as a handbook to AISC 370, advises on the durability of different stainless steel alloys in various environments.

S32205 is the most commonly used standard duplex alloy for structural members in bridges and it provides a significant increase in corrosion resistance over the common austenitic stainless steels or lean duplexes. Lean duplexes such as S32003, S32101, S82011, and S32202 provide corrosion resistance similar to, or better than, austenitic stainless steel S31603.

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 S31600/S31603 bolts should be used for connecting lean duplex plate, and duplex S32205 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 bushings 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 slip critical bolted assemblies are not significantly higher than those for equivalent connections made of carbon steel. AISC 370 gives design rules for slip critical connections, with slip factors for different stainless steel surfaces. The installation parameters used in the pre-installation verification may be developed using the bolt tightening qualification procedure provided in AISC Design Guide 27.

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 2 in. (50 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 180 ft (55 m) and is 43 ft (13 m) wide (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 S32205 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 6 ft (2 m)) working compositely with a reinforced concrete deck. The arches have a triangular cross-section with a constant depth of 28 in. (700 mm), while the longitudinal and transverse beams were made of rectangular hollow sections with dimensions of 20x39 in. (500x1000 mm) for the former and up to 10x22 in. (250x570 mm) for the latter. All cross-sections were welded from plates with thicknesses ranging from 0.4 in. to 1 in. (10 mm to 25 mm) [3]. The balustrades were also made from duplex stainless steel S32205, while austenitic stainless steel S31603 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 S32205 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 [4],[5]. 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.

The new bridge is a 130 ft. (40 m) span open-spandrel arch bridge, carrying a single-lane road and two pavements, of width between 25 and 31 ft (7.5 and 9.5 m). Welded shear studs enable the 5/8 in. (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.

The high strength of duplex stainless steel helped to minimise the weight of the bridge. The entire structure - 88 tons (80 tonnes) stainless steel, 240 tons (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, using duplex stainless steel S32101 for the main structure and handrails

(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 stainless steels 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 the US, the technical requirements for the design, fabrication and erection of stainless steel structures is covered by the new specification ANSI/AISC 370 *Specification for Structural Stainless Steel Buildings* [1]. AISC 313 *Code of Standard Practice for Structural Stainless Steel* [6] is a companion specification which sets out the responsibilities of each member of the construction team and the standards of quality required of fabricators and erectors. AISC Design Guide 27 gives worked examples and tables of section properties and member capacity tables for a range of structural sections.

Relevant ASTM product specifications include ASTM A240 for plate [7], ASTM A276 for bars and shapes [8], and ASTM 1069 for laser welded built-up shapes [9]. These specifications give the chemical composition and technical requirements of the different stainless steels that are used in structural applications.

The most common standard for smaller diameter up to 1½ in. (38 mm) austenitic stainless steel bolts is ASTM F593 [10]. Other standards are available for specifying bolt diameters over 1½ in. ASTM A1082/A1082M [11] covers duplex stainless steel bolts.

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 630 ft (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 S82441 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 ($4.6 million compared to $2.3 million), 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 dollars. 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 [12].

Fig 4 Söderström Rail Bridges fabricated in lengths of 52-75 ft (16-23 m)

(Photo: Lars Hamrebjörk)

References

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[8] ASTM A276/A276M Standard Specification for Stainless Steel Bars and Shapes

[9] ASTM A1069/A1069M Standard Specification for Laser and Laser Hybrid Welded Stainless Steel Bars, Plates, and Shapes

[10] ASTM F593 Standard Specification for Stainless Steel Bolts, Hex Cap Screws, and Studs

[11] ASTM A1082/A1082M Standard Specification for High Strength Precipitation Hardening and Duplex Stainless Steel Bolting for Special Purpose Applications

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