Sustainable Duplex Stainless Steel Bridges

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Abstract Duplex stainless steels are increasingly used as structural materials in building and architecture because of their exceptional mechanical properties. Their room temperature yield strength in the solution annealed condition is more than twice that of standard austenitic stainless steels not alloyed with nitrogen. Over the last few years, they have started playing an increasingly important role in the construction of bridges, wherever specific environmental conditions combine with the need for high load-bearing capability. Duplex stainless steels are mostly selected because of their combination of high strength and corrosion resistance. Their full potential is used in locations where the material comes into contact with salt water, or where high concentrations of chlorides are present in the ambient air or where de-icing salts are of a concern. The higher initial costs involved in choosing duplex stainless steel as compared to conventional structural steel are more than compensated by longer life span and significantly lower maintenance and repair costs. Their full recyclability makes them more sustainable than non-metallic solutions. Several recent examples of using duplex stainless steels in bridge construction are presented.

1 What is a sustainable bridge?

Sustainable development, which ‘meets the needs of the present without compromising the ability of future generations to meet their own needs’ [1] requires a balancing of environmental, social and economic demands. This is illustrated in Figure 1 where the overlapping ellipses indicate that the three priorities of sustainability are not mutually exclusive and can be mutually reinforcing [2].

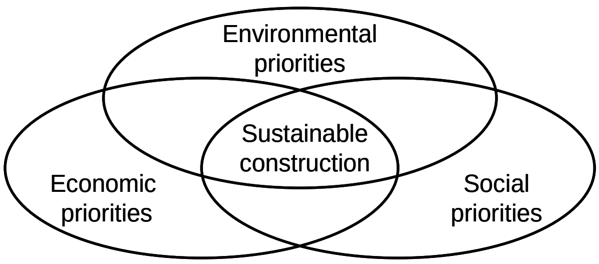

Fig. 1. Sustainable construction – meeting three priorities

Key themes of sustainable construction can be summarised below:

- design for minimum waste,
- aim for lean construction,
- minimise energy in construction and in use,
- avoid pollution,
- preserve and enhance biodiversity,
- conserve water resources,
- respect people and their local environment.

Sustainability is now a priority in the design, construction and maintenance of the civil engineering structures which make up the infrastructure in most parts of the world. Bridges can satisfy the three priorities of sustainability by:

- being economical in terms of their entire lifetime, including decommissioning, and also considering the effects of user disruption during construction and maintenance.
- meeting social priorities, considering both the construction workers, and the people living near to and using the bridge.
- minimising environmental impact in terms of carbon dioxide emission and embodied energy during fabrication and construction and ensuring as many bridge components as possible are recyclable and preferably re-usable at the end of the bridge's life.

2 Relevant properties of duplex stainless steels for bridge structures

Duplex stainless steels have many desirable characteristics which can be exploited in bridge applications. The three grades most suitable for use in bridges are 1.4462, 1.4362 and 1.4162 to EN 10088-4 [3]. The principal properties of interest to bridge designers are:

Strength: These duplex stainless steels have design strengths between 400 and 460 MPa, 15 to 30% stronger than the design strength of grade S355 carbon steel that is generally used in bridges. Unlike carbon steel, no reduction in design strength for plate thickness exceeding 16 mm is required.

Ductility: Ductility is a measure of the capacity of a material to elongate under tensile loading before fracture occurs. Duplex stainless steels display high levels ductility (at least 25% for plates), which compare favourably with the relevant carbon steel grades.

Toughness: All steel bridge components subject to tension must achieve a specified notch toughness in order to prevent brittle fracture. This depends on the minimum design temperature, stress level and material thickness. Duplex stainless steels display a more gradual ductile to brittle transition than carbon steels and retain their toughness down to around -40 °C. (Minimum impact toughness values in the transverse direction at -40 °C are 27 J for 1.4162 and 40 J for 1.4362 and 1.4462 [4], which compare favourably to carbon steel.)

Weldability: Duplex stainless steels can be welded using a number of widely available processes; provided correct welding procedures are followed, this method of joining should be no more difficult than with carbon steel.

Fatigue resistance: The resistance of duplex stainless steels is at least as good as carbon steels.

Durability: The high chromium content of duplex stainless steels, along with molybdenum and nickel, give them very good resistance to chloride-induced pitting and crevice corrosion. All duplex stainless steels grades show very good resistance to stress corrosion cracking (SCC). It is important that the chosen grade of duplex stainless steel is appropriate for the intended service environment since the price of the material generally increases with the corrosion resistance. Table 1 gives some guidelines.

Table 1 Guidelines for duplex stainless steel selection

ISO 9223 Atmospheric Corrosion Class	**Typical outdoor environment**	**Suitable duplex grade**
C1	Deserts and arctic areas (rural)	1.4162
C2	Arid and low pollution (rural).	1.4162, 1.4362
C3	Costal areas with low deposits of salt. Urban or industrialised areas with moderate pollution.	1.4162, 1.4362, (1.4462)
C4	Polluted urban and industrialised atmosphere. Costal areas with moderate salt deposits. Road environments with de-icing salts.	1.4462, (1.4362), other more higher alloyed duplexes
C5	Severely polluted industrial atmospheres with high humidity. Marine atmospheres with high degree of salt deposits and splashes.	1.4462, other more higher alloyed duplexes
Grades suitable for a higher class may be used for lower classes but might not be cost-effective. Grades within brackets denote use/need in special cases.		

3 Environmental benefits of duplex stainless steel bridges

3.1 Energy and CO_2 burdens

Two major quantifiable measures of environmental sustainability of construction activities are the parameters of energy consumption and CO_2 emissions. The unit weight 'embodied' values of these burdens for duplex stainless steels are higher than for carbon steels. However, this does not take into account the fact that a duplex structural element is likely to be lighter than its carbon steel equivalent in load-bearing terms. A comparative Life Cycle Assessment (LCA) of a range of bridges designed in duplex stainless steel, carbon steel, concrete, masonry etc is needed in order for the energy consumption and CO_2 emission to be rigorously evaluated and compared on a scientific basis. Some work has been done in this area on austenitic stainless steels but not for duplex stainless steels [5].

3.2 Recycling and re-use

Stainless steel is 100% recyclable without any loss of performance or change in material properties. This benefits the environment by reducing the depletion of non-renewable resources, reducing the energy consumption in manufacturing, and avoiding end of life disposal impacts. It is estimated that at least 70% of stainless steels are recycled at the end of their life (one of the highest recycling rates of any material). Re-use rather than recycling lessens the impact even further, since the high energy burdens of re-melting and re-fabricating are avoided. Bolted connections clearly simplify deconstruction and facilitate re-use.

3.3 Lightweight construction

Duplex stainless steel has a high strength to weight ratio which enables the specified load-bearing constraints to be met with a lighter and thinner structure, often looking better than a bulky concrete alternative. It also reduces the inertia effects induced by seismic events. Larger spans are possible, which eliminate the need to build supports in the middle of a road or river, simplifying construction and reducing the need for a hazardous work environment. This also cuts down the environmental impact on rivers, as well as removing a hazard for boats. Lighter construction reduces the required foundations, reducing construction times and minimising ground disturbance, in turn lowering the excavation, transportation and disposal costs. This is especially useful where the bridge is on soft ground, such as a river estuary.

The reduction in weight will reduce CO_2 emissions and energy use both directly in less materials used and also indirectly due to lower transportation costs.

3.4 Minimising waste

Computer aided design and workshop prefabrication optimise the quantity of material used and generates a minimum of waste which, moreover, is recovered and recycled.

4 Economic benefits of duplex stainless steel bridges

4.1 Efficient use of resources

A bridge is a major investment. The choice of material must offer a good balance between minimising weight, deflection, dynamic response and susceptibility to fatigue over the life of the bridge. There is a correlation between cost and environmental burden for bridges; an efficient design minimises costs and environmental burdens. Whilst the initial ‘costs’ are useful, it is the ‘cost/energy use’ over the structure’s full life that is more significant. A life cycle approach, taking into account the construction, operation, maintenance and deconstruction costs, over its entire lifetime, may well compensate for the higher capital cost linked to the choice of duplex stainless steel in certain circumstances.

Reference 6 describes life cycle costing performed for small road bridges. The study concluded that the application of stainless steel was cost-effective for crowded roads with daily traffic of over 20,000 vehicles.

Note that it is possible to restrict the use of stainless steel to external parts and to use carbon steel for the internal, unexposed parts (this is the choice that was made for the Pedro Arrupe footbridge in Bilbao where the internal structure is carbon steel.) However, the two types of steel must never come into direct contact and access to the structure’s internal parts must be possible in order to conduct regular inspection.

4.2 Factory production

At present, it seems that the costs for stainless steel fabrication are disproportionately more expensive than the same fabrication in carbon steel. The reasons for this disparity cannot be easily explained on the basis of material cost and or increased fabrication cost alone. It has been suggested that this topic needs further investigation [7].

4.3 Adaptability

Stainless steel bridge solutions are generally readily adaptable to suit changes in road configurations and increased loading, ensuring that they are used for the full intended design life. They can be widened, strengthened and lengthened, or the entire bridge can be moved to a new location. For example, more girders can be added alongside existing girders, flange sizes can be increased by welding or bolting on additional plates. This is important considering the long life of steel bridges – 100 years or more – as there could well be a change in demand that was not predicted during the design process.

4.4 Durability and maintenance

Bridge maintenance, and the inevitable resultant traffic congestion, have both a cost and environmental impact. Designing low maintenance bridges is quite a challenge considering that the principal structural components are exposed for long design lives. Durable, long life structures represent substantial savings in the cost of maintenance and replacement of components. With good detailing and correct grade selection for the service environment, duplex stainless steel bridges compare very favourably against carbon steels. The absence of coating reduces environmental burdens at the outset and throughout the life of the structure.

Duplex stainless steel bridges can be repaired whilst remaining in service. The ductility and toughness of duplex stainless steel allows absorption of loading well above design values without catastrophic failures.

4.5 Disruption during construction

Steel construction involves fewer site deliveries and a shorter construction programme than in situ concrete construction. This can be especially beneficial in reducing the disruption to road users and the environmental burden due to longer journeys during the construction period.

5 Social benefits of duplex stainless steel bridges

5.1 Factory production and skills development

A duplex stainless steel bridge can be built with a minimum of disruption; it can be partially constructed offsite, and then the final modules assembled on site, or in some cases, the entire bridge moved into place as a whole. This can be important if the new bridge is replacing an existing one that is nearing the end of its life, as the switch can be made in only a few days, minimising disruption to bridge users. Less time onsite reduces the disruption to the local community if the bridge is in a populated area.

The greater use of off-site construction activities has the benefits of reduced hazards for the workers (avoiding or reducing the need to work at heights or in riverbeds) and the use of established facilities and communities, rather than the use of an itinerant workforce. The workers can have continuous indoor work at factories in a fixed location, rather than following construction around the country; this promotes stable families and communities by giving people jobs near to where they live.

Use of integrated computer modelling and numerically controlled fabrication equipment ensures a high degree of accuracy of components, minimising problems during site assembly and thus reducing hazards.

5.2 Health and safety

The predominantly off-site nature of bridge steelwork construction promotes a culture of safe and healthy working practices. Site activities are usually undertaken by a specialist workforce using specialist plant, which promotes the establishment of trained teams, with consequent improvements in safe working practices.

Duplex stainless steels do not require intensive maintenance, unlike painted materials.

5.3 Appearance

Social demands often lead to the choice of a particular form for its 'better appearance'. This could result in a structure with a slightly higher environmental burden but its impact in relation to the users or society in general may be lessened.

Steel and, more recently, stainless steel are natural choices for landmark bridges. They are suitable for creating complex geometries, including horizontally curved and skewed alignments. The range of surface finishes which can be applied to duplex stainless steels, from standard mill finishes to different types of polished finishes, can also be used to achieve a specific aesthetic effect.

6 Examples of duplex stainless steel bridges

Although it is only over the last ten years that duplex stainless steels have been used in bridge structures, the range of applications already demonstrates the potential for much greater use. Table 2 lists bridges constructed over the last ten years which incorporate main structural elements made from duplex stainless steel.

The Cala Galdana Bridge in Menorca was the first stainless steel road bridge in Europe (Figure 2). 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.

The upper 118 m of the 300 m high towers of the Stonecutters Bridge in Hong Kong are composite sections with an outer duplex stainless steel skin and a reinforced concrete core (Figure 3). In a marine environment and in a typhoon belt, as well as being near a major city and the port of Hong Kong, the towers needed to have minimal maintenance requirements for the bridge's 120 year life, as such work would be costly, dangerous and disruptive to the high expected traffic flow.

The first hybrid duplex stainless steel/glass fibre reinforced plastic (GFRP) pedestrian bridge was constructed in Zumaia, Spain over the Narrondo River, connecting a school with sports facilities on the other side of the river (Figure 4). The client required a lightweight structure with good durability as the footbridge is located close to the sea. Grade 1.4462 duplex stainless steel was chosen.

The Helix Bridge in Marina Bay, Singapore, is a landmark pedestrian bridge. The bridge is the world's first double-helix pedestrian bridge: two helixes, built from stainless steel pipes, spiral around each other to form the core of the 280 m structure (Figure 5). It is estimated that a conventional box girder bridge would have used five times the weight of steel.

The Piove di Sacco Bridge in Padua, Italy spans 120 m. The deck is supported by two 1300 mm diameter arches made of 12 to 26 mm thick 1.4362 duplex stainless steel plate (Figure 6).

Meads Reach Bridge, winner of a RIBA 2009 award, is a 55 m, stressed skin arc across the river (Figure 7). Stainless steel plates form the steel bridge deck and perforated flanks.

Table 2 Bridges using duplex stainless steel

Date	Name and location	Type of bridge	Duplex stainless steel components and grade
1999	Suransuns Bridge, Switzerland	Stress ribbon pedestrian bridge, 40 m span	Four structural ribbons 1.4462
2001	Millennium Bridge, York, UK	Tilted box girder arch pedestrian bridge 80 m main span	Arch 1.4462
2002	Apate Bridge, Stockholm, Sweden	Tied beam pedestrian bridge	Main girder 1.4462
2003	Kungalv, Sweden	Arch rail bridge, upgrade	Replacement of corroded carbon steel deck hangers (after 8 years service) 1.4462
2003	Pedro Arrupe Bridge, Bilbao, Spain	Box girder pedestrian bridge Total length 140 m	Box girder with carbon steel internal structure 1.4362
2004	Likholefossen Bridge, Norway	Lightweight pedestrian bridge, 24 m span	All except concrete columns 1.4162
2004	Viaduct Črni Kal, Slovenia	Continuous pre-stressed concrete road bridge. Length 1056 m, 140 m maximum span	Wind barrier from tubular sections (110 tonnes). 1.4162
2005	Cala Galdana Bridge, Menorca	Arch road bridge, 45 m main span	Main structure, including the 2 arches (160 tonnes) 1.4462
2005	Arco di Malizia, Siena, Italy	Single arch road suspension	Arch 1.4362
2006	Siena Bridge, Ruffolo, Italy	Cable stayed pedestrian bridge 60 m span	Load bearing structure 1.4162
2006	Piove di Sacco Bridge, Padua, Italy	Dual arch road suspension	Arches, deck and casing (110 tonnes) 1.4362
2006	Celtic Gateway Bridge, Holyhead, Wales	Arch pedestrian bridge Total length 160 m, main span 70 m	Load bearing arch (220 tonnes) 1.4362
2008	Zumaia Bridge, Spain	Pedestrian bridge, length 28 m with a 5 m wide deck.	428 components and 3 plates (20 tonnes) Composite GRFP and 1.4462

Date	Name and location	Type of bridge	Duplex stainless steel components and grade
2009	The Helix, Marina Bay, Singapore	Tubular pedestrian bridge Total length 280 m	Main structure (400 tonnes structural pipes; 200 tonnes other structural parts) 1.4462
2009	Stockfjarden outlet in Flen, Sweden	Road bridge	Load bearing I beams 1.4162
2009	Meads Reach, Bristol, UK	Stressed skin arc pedestrian bridge, 55 m span	Stressed skin arc (75 tonnes) 1.4462
2009	Sant Fruitos Bridge, Spain	Pedestrian arch bridge	All load bearing structural elements 1.4162
2009	Stonecutters Bridge, Hong Kong	Cable-stayed road bridge 1,596m total length 1,018 m longest span	Outer skin of the towers (1800 tonnes plate 200 tonnes pipes) 1.4462
2010	Second Gateway Bridge, Brisbane Australia	Road bridge over river	Reinforcing bar in concrete pile caps 1.4162
2011	Harbor Drive Pedestrian Bridge, San Diego, US	Pedestrian bridge 162 m curved span	1.4462

7 Conclusion

Transport networks are of crucial importance to economic growth. It therefore makes sense to ensure that bridges are designed to high levels of sustainability to prevent deficiencies in their durability or strength necessitating repair or replacement that would lead to considerable disruption for their users. A sustainable bridge is a structure that has been built quickly but efficiently to last a long time, with optimal use of resources as well as minimal disruption of the surrounding environment and minimal wasted materials. Bridge designers around the world are seeking high performance materials that can be used in the construction of bridges and which offer extended service life, lower energy requirements and simplified deconstruction at end-of-life.

Duplex stainless steels have tremendous potential for expanding future applications in bridge structures; their high strength, toughness and ductility coupled with excellent durability should lead to many future applications in sustainable bridges. Further work is needed in order to quantify the relative environmental impacts of duplex bridges compared to conventional materials for bridges.

Fig. 2. Cala Galdana Road Bridge, Menorca (Courtesy: Pedelta)

Fig. 3. Stonecutters Bridge: monotower and stay cables (left), segment of skin (top right), shear connectors on side of tower segment (bottom right) (Courtesy: Arup)

Fig. 4. The Helix, Marina Bay, Singapore (Courtesy: Darren Soh)

Fig. 5. Zumaia Pedestrian Bridge (Courtesy: Pedelta)

Fig. 6. Piove di Sacco Bridge under construction, Padua, Italy (Courtesy: Centro Inox)

Fig. 7. Meads Reach Bridge, Bristol, UK (Fabricator: www.m-tec.uk.com, Photo: www.photo-genics.com)

References

1. United Nations General Assembly Report of the World Commission on Environment and Development: Our Common Future (1987)
2. United Nations General Assembly. 2005 World Summit Outcome, Resolution A/60/1, adopted by the General Assembly (2005)
3. EN 10088-4 *Stainless steels. Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for construction purposes* (2009)
4. Duplex stainless steel, Outokumpu brochure, 1008EN-GB:6, www.outokumpu.com (2008)
5. R.A. Daniel, *Environmental considerations to structural material selection for a bridge*, European Bridge Engineering Conference, Lightweight Bridge Decks, Rotterdam (2003)
6. A. Beletski, *Applicability of stainless steel in road infrastructure bridges by applying life cycle costing*, Masters Thesis, Helsinki University of Technology (2007)
7. G. Gedge, *Structural uses of stainless steel – buildings and civil engineering*, Journal of Constructional Steel Research (2008)