

STAINLESS STEEL IN BRIDGES: A DISCUSSION

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ABSTRACT

In New Zealand, stainless steel is rarely used in bridges, other than in bearings, as hand railings, or as architectural components to highlight features on the bridge. However, internationally its use has been increasing in the past decade not only as an architectural feature but also as some of the main structural components of the bridge.

This paper looks at the use of different stainless steel components in bridges, from railings, steel decking, concrete reinforcement and to structural beams. This discussion includes life cycle costing comparison, taking into account future maintenance, in different corrosivity environments over the 100 year design life of the bridge structure. Case studies from New Zealand and overseas are given, in addition to guidance on the selection, fabrication, erection and maintenance of stainless steel to ensure the optimum performance over the usually required 100 year design life.

Introduction

Stainless steel is commonly used in New Zealand in several different industries, such as the food and water industries; however, its use in construction and especially bridges is limited. In bridges, stainless steel has been used in footbridges as hand railing, as an architectural feature (see Figure 1) or as a sliding surface in road bridge bearings. In all these instances, stainless steel was chosen for aesthetics, or its long service life and, when designed and detailed correctly, its low maintenance requirements.



Figure 1: Stainless steel lattice tower on Ormiston Bridge in Auckland.

In New Zealand, its use in other areas in bridges, such as concrete reinforcement and as main girders, is still seen as an expensive option in comparison to conventional uncoated reinforcement or coated carbon steel structural members. This perception is one of the main barriers that are inhibiting its use, since once it is suggested as an alternative option the first reaction is its dismissal as “too expensive”. By conducting a comprehensive life cycle costing for each option, taking into account the bridge function, maintenance, traffic disruptions, and even the demolishing and recycling of the structure at the ends of its life, a more accurate comparison can be made that demonstrates its cost effectiveness.

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Internationally the use of stainless steel in bridges has been increasing, as seen by a number of high profile bridge projects such as the Simone-de-Beauvoir Footbridge in Paris, France and The Helix Bridge in Singapore (Figure 2). This paper looks at the differences between conventional steel components and stainless steel and the alternative uses of stainless steel in bridges, which includes case studies. An overview on calculating the life cycle costing of different options is also given, with the paper concluding with a summary of the design criteria that the bridge designer should be aware of to achieve the desired optimum performance.



Figure 2: The Helix Bridge in Singapore.

Conventional Steel versus Stainless Steel

All bridges utilise steel in one form or the other, whether as reinforcement, bolts or as structural members. Conventional carbon steel components have a proven track record of performance; however this is dependent on the correct design, specification, fabrication and installation. The main disadvantage of conventional steel is the requirement for their protective coating's refurbishment or replacement during or after the life span of the structure. Over the 100 year design life of the bridge its structural members (such as a steel girder, Figure 3) will require a recoat or repair of the original corrosion protection coating. While for concrete components (Figure 3), the steel reinforcement may have developed signs of corrosion that is usually expensive to arrest and repair.



Figure 3: Example of corroded steel girders and concrete reinforcement.

Corrosion protection technologies in both steel and concrete structures has seen continuous improvements, especially in the last couple of decades, with longer expected time to first maintenance for coatings and better concrete mixes with higher strength and impermeability, or the use of impressed cathodic protection, all providing better protection for reinforcement. Regardless of these advancements, regular maintenance is still required (e.g. removal of wind-borne marine salts by pressure washing). Also periodic major refurbishment by patch painting such as on the Auckland Harbour Bridge, or in some cases full removal and replacement of the coating system as proposed for the Makatote Rail Viaduct, and in the case of a concrete bridge, major repairs or in the case of the Tiwai Access Bridge, total replacement.

To address this issue, the use of stainless steel should be considered at design. Similar to conventional steel components, stainless steel also requires the correct design, specification, fabrication and installation. Once these are satisfied, its maintenance requirements are significantly less, and in most cases, regular inspection and washing could be the only "maintenance" required over the 100 year design life of the

structure. The following sections will discuss the different topics that should be considered by the designer when considering the use of stainless steel in a bridge.

Alternative Uses of Stainless Steel Components

Alternatives uses of stainless steel components that should be considered are:

Reinforcement

The use of stainless steel reinforcement has been steadily increasing in the past decade. One of the main failure modes of conventional reinforcement is the migration of chloride ions through porous concrete with time. These chloride ions then initiate corrosion of the reinforcement, which will cause the loss of the reinforcement thickness and the concrete to spall. This in turn reduces the overall capacity of the concrete member and if not repaired, it's premature failure.

By using stainless steel reinforcement, such as duplex 2205 stainless steel, this failure mode is mitigated thereby ensuring the long term performance of the concrete member (Cochrane 2003). Guidance on the use of stainless steel reinforcement is now available from Part 15 of the UK Highway Agency Design Manual for Roads and Bridges (Highway Agency 2002).

New Zealand currently has one example of a railway culvert that utilises duplex 2205 stainless steel reinforcement. The culvert is located in Wellington Harbour (Figure 4) and is partly submerged in sea water; hence to achieve 100 year design life, the use of stainless steel was chosen to provide dependable long term performance with minimal maintenance requirements (Spooner 2013). The life cycle costing on the use of conventional reinforcement versus stainless steel is given below.

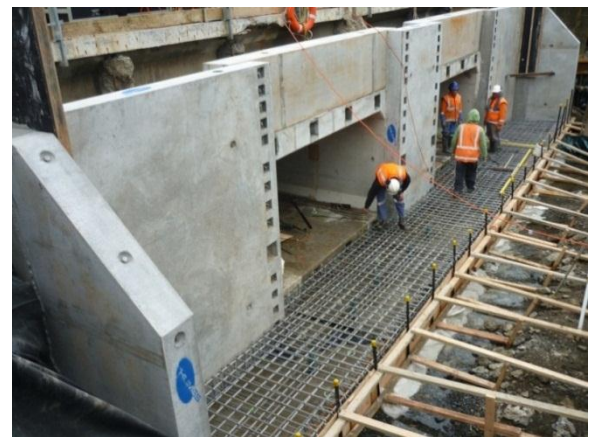


Figure 4: Wellington Harbour Culvert stainless steel reinforcement cage.

It should be noted that a more economical option is the use of stainless steel reinforcement on the outer layers of the reinforcement cage, with conventional steel reinforcement on the inner layers. The reason being is that the outer layers are used in the zone where chloride ions will ingress over time, which theoretically will not reach the inner layers over the design life of the structure. The risk of galvanic corrosion is reduced by the alkalinity of the concrete, which will passivate the mild steel, thereby forming a protective layer that also mitigates galvanic corrosion between the dissimilar metals (NRCC 2005).

Stainless steel reinforcement should always be used in those components of reinforced concrete marine structures where conventional repairs cannot be carried out in the future (Markeset 2000).

Steel Decking

Composite steel decking is commonly used in multi-story buildings as a floor decking system, which has seen an increase in its use in car parks and pedestrian bridges in recent years. It consists of an in situ reinforced concrete topping placed on galvanized profiled steel cladding material that not only acts as a permanent formwork, but also provides shear bond with the concrete via shear studs, allowing both materials to work compositely together. This decking system provides a number of advantages such as being easy to handle onsite allowing for reduced construction time, reduced onsite craneage requirement and provides a lighter decking alternative than other conventional systems.

However, as a bridge component, steel decking has to achieve a 100 years design life to satisfy the Bridge Manual (NZTA 2003) requirements. Therefore the galvanized decking will require the use of an additional protective coating system which, depending on the structures location, will need to be recoated a number of

times over the 100 year design life. By considering the future maintenance cost, access, health and safety, and the potential environmental impact associated with recoating, stainless steel can provide a cost effective option, especially where future recoating is difficult to carry out. In this case, the ferritic 445M2 stainless steel grade provides a cost effective alternative with similar strength and bending properties as the galvanized steel option.

William Harvey Place Footbridge is a good example of stainless steel decking application (Figure 5). It is a 38.8 metre single span steel arch bridge spanning over an electrified railway corridor and the motorway. Steel decking was chosen to enable the bridge span to be lifted into place at a significantly reduced weight, and the concrete topping could be poured after erection (Xia 2013).

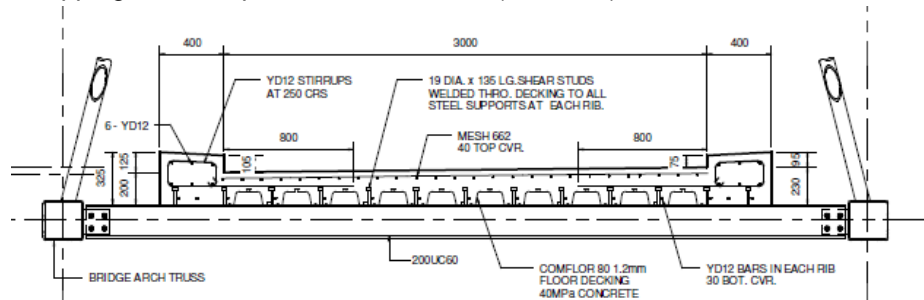


Figure 5: Cross section of main span.

The bridge is located in a corrosive marine environment, thereby requiring the galvanized steel decking to be recoated approximately every 25 years. The recoating work in this case would be very costly due to the bridge being located above the electrified railway corridor, thereby requiring the closure of the railway line during the recoating of the decking soffit. To address this issue, a stainless steel option has been proposed, where the only maintenance required will be regular washing of the decking that can be done during the annual inspection of the bridge.

Preliminary life cycle costing indicates that the ferritic stainless steel decking material is approximately 4 times more than the equivalent galvanized steel decking. Once the cost of applying the additional coating system was taken into account, the cost difference was reduced to a 30% premium for the stainless option. When taking into account future maintenance of the coating system as well, the stainless steel option provides similar costing in net present value terms.

Structural Cladding

Stainless steel cladding is typically used as an aesthetic feature in different types of structures; however designers should also consider the use of stainless steel plate as structural components on bridges. In this case, as part of a bridge substructure as in piers columns or towers in cable stayed bridges. This could be as stand-alone structural components or acting compositely with a concrete core.

A good example of this application is the Stonecutter Bridge towers in Hong Kong, where the corrosive marine environment, coupled with nearby industrial pollutants and difficult site access, required a durable long term solution with minimal maintenance. To achieve these requirements, 1600 tonnes of 2205 duplex stainless steel (20mm and 25mm) plate was chosen as part of the cable stayed towers (Vejrum et al 2009). This stainless steel plate was acting compositely with the concrete core thereby providing a superior structural member than using conventional methods (Figure 6).



Figure 6: Stonecutter Bridge stainless steel clad tower in Hong Kong.

Structural Components in Cable Stayed Bridges

In the case of cable stayed bridges, stainless steel could be used as part of the cable stayed connection components. This was recently specified on the San Diego Harbor Drive Pedestrian Bridge (Figure 7), which is located in a marine environment; where the stainless steel railing was used connect the stainless steel hangers to the suspension cables (Houska et.al. 2012). An interesting note on its design is that the hangers generated an inward compression force on the cable which can only act in tension, therefore stainless steel hollow circular sections were used to resist this inward compression force thereby keeping the cable in pure tension. In this case, stainless steel provided the required strength and corrosion resistance in addition to aesthetics.



Figure 7: San Diego Harbour Drive Pedestrian Bridge suspension cable stainless steel components.

Structural Girders

Structural steel beams have conventionally used mild steel with a protective coating system, with weathering steel being a relatively recent development with a limited number of road and railway bridges built locally to-date. Both materials have seen resurgence in the past 6 years in New Zealand; however, designers should also consider the use of stainless steel as structural girders as well. Its use in both pedestrian and road bridges have been increasing overseas (ArcelorMittal 2010), where its benefits are being realised. In this case, it is suggested that the lean duplex LDX2101 stainless steel can be used for footbridges, while the duplex 2205 grade, with its higher fatigue resistance and strength can be used for road bridges.

The Cala Galadana Bridge on the Island of Menorca, Spain, provides a good example on the use of structural stainless steel. Completed in 2005, the bridge replaced a conventional concrete bridge built in the early 1960's that was at the end of its useful life after years of exposure to warm, humid, saline air and to sea spray and sand abrasion (Millbank 2005). Stainless steel was chosen as it provided a durable, low maintenance structure and aesthetically pleasing with a low environmental impact. Even though the cost of the 55m long, 13m wide low arch bridge is €2.4million, it was deemed to be a cost effective option in the long term. A total of 162 tonnes of duplex 2205 stainless steel plate was used in stainless steel arches, girders (Figure 8) and handrails, with a concrete composite decking.



Figure 8: The underside of the Cala Galadana Bridge in Menorca.

Life Cycle Costing

There are different life cycle costing models that can be used, of which the most common method in New Zealand is the Net Present Value (NPV) method. This model takes into account the initial construction cost followed by the expected maintenance cost throughout the design life of the bridge. This incorporates a discount rate of 8% for 30 years (NZTA 2010), which modifies the future maintenance cost, into "today's dollars" taking inflation as being 0%. However, current discussions in the construction industry have suggested that this factor should be reduced to 4% which would provide a more realistic life cycle cost in the current low interest rate environment. The equation for the net present value is:

$$NPV = IC + \sum_t^T \frac{OC}{(1+DR)^t} \quad (1)$$

Where:

NPV = Net present value.
 IC = Initial construction cost (material, fabrication, erection, etc).
 T = Design life in years (usually 100 years for bridges).
 t = Operation time in years.
 OC = Operating maintenance cost.
 DR = Discount rate.

Another model has been proposed by the International Chromium Development Association, Euro Inox and the Southern Africa Stainless Steel Development Association (2005). In this model in addition to the initial construction cost and expected maintenance cost, the lost production cost during down time (such as traffic disruption) and replacement cost of the structure is also taken into account. Therefore, this equation is:

$$LLC = IC + \sum_t^T \frac{OC}{(1+DR)^t} + \sum_t^T \frac{LP}{(1+DR)^t} + \sum_t^T \frac{RC}{(1+DR)^t} \quad (2)$$

Where:

LLC = Life cycle cost.
 LP = Loss of production costs during down time.
 RC = Replacement cost.

Both models are basically the same, except that the latter provides a more comprehensive costing. This is especially true for bridges, as after the 100 year design life the structure is supposed to be replaced with a new one. Following the philosophy that after 100 years structural stainless steel bridge components will have:

- Lower maintenance cost, since there is no coating to be refurbished, with the only maintenance being washing.
- Due to the low maintenance, lost production cost is low or even can be taken as zero.
- Properly designed and maintained stainless steel components will probably not require replacing at the end of the design life, thereby possibly extending the design life beyond the 100 years.

Therefore which model is used will affect the results when undergoing a life cycle costing between different structural materials. While, the second more comprehensive model will likely favour stainless steel, the first simpler net present value model should demonstrate that stainless steel is economical in the long term due to the lower maintenance cost. Figure 9 demonstrates a typical cost patterns throughout the design life of the structure between stainless steel and other structural materials (whether concrete or carbon steel). As seen in Figure 9, the initial cost of using stainless steel is higher than that of other materials, but as maintenance is undertaken throughout the years, cost savings are realised.

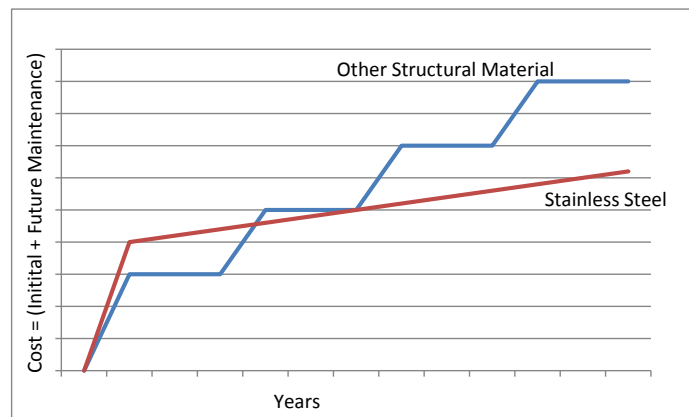


Figure 9: Typical life cycle costing of stainless steel versus other structural materials.

A New Zealand example of life cycle costing using the net present value is the Wellington Harbour Culvert, where the cost of the stainless reinforcement was 4 times that of conventional carbon steel reinforcement for supply, cutting, bending and fixing. Since the culvert is located in Wellington Harbour (Figure 10) and continuously exposed to sea water the cost of protecting conventional carbon steel (using thicker concrete

cover, concrete mix and additives) resulted in the initial project cost of the stainless option being reduced to being 16% more in comparison to the conventional reinforcement. However, once the total life cycle costing was taken into account, the net present value of the stainless steel option was found to be 8% lower than the conventional option, taking into account the future refurbishment and/or replacement of some segments of the conventional reinforcement option.



Figure 10: Wellington Harbour Culvert.

It should be noted that in most cases, stainless steel will demonstrate its cost effectiveness in highly corrosive atmospheric environments, whether marine or industrial. Once the bridge is located outside these environments, other structural materials may prove to be more economic due to the longer expected time to first maintenance. An alternative option is the selective use of stainless steel components with other materials, which will assist in the reduction of the initial cost difference. As mentioned previously, this could be as simple as selective use of stainless steel reinforcement on the outer layers of a concrete substructure with an inner core of carbon steel, or the use of stainless steel permanent formwork decking instead of a galvanized decking option. Either way, undertaking a life cycle costing from the early stages of the project is important, even if the Client requests a stainless steel option for aesthetics purposes or when requesting an “iconic” structure.

Maximising Optimum Service Performance

To achieve the maximum potential of using stainless steel, a number of design and construction items should be considered from the early design stage to the completion of the structure. These items are summarised below and are given in greater detail in numerous publications and practice notes available from different organisations, such as the New Zealand, Australian or European Stainless Steel Development Associations, Euro Inox and the North American Nickel Institute.

Mechanical Properties and Design

There is a wide range of different stainless steel alloys, with more being developed every year. The two grades discussed in this paper, duplex 2205 and lean duplex LDX 2101, are just two examples of what can be used. It should be noted that all stainless steel, in comparison to conventional carbon steel, has a non-linear stress-strain behaviour, even for reduced stress values, without a clearly defined elastic limit. Therefore, the stress associated with a strain of 0.2% is adopted as a conventional elastic limit. An example of the different mechanical properties of duplex 2205, lean duplex LDX 2101, the so-called “marine grade” austenitic 316 and Grade 350 carbon steel is given in Table 1. It should be noted that the European designation to the Eurocode are now commonly being used outside New Zealand, so the American (ASTM) and European (EN) designations are both given in Table 1.

Table 1: Minimum mechanical properties of different grades of stainless steel and Grade 350 carbon steel.

Property	Stainless Steel Grade (ASTM/EN)			G350 Carbon Steel
	316/1.4401	LDX 2101/1.4162	2205/1.4462	
Tensile Strength (MPa)	510	650	680	510
0.2% Proof (Yield) Stress (MPa)	220	450	480	350
Elongation to Rupture (%)	45	30	25	>15

As shown in Table 1, both duplex and lean duplex grades of stainless steel have higher yield capacity than conventional Grade 350 carbon steel thereby allowing thinner plates to be used when deflection or serviceability requirements do not govern design. This in turn reduces the overall weight of the steel structure resulting in cost savings in both the super- and substructure. Furthermore, the duplex 2205 has better fatigue resistance than the lean duplex LDX 2101 grade; hence it is better suited for road traffic loading, while the latter is recommended for pedestrian bridges when stainless steel plates as structural members are used. All three stainless grades given in Table 1 are suitable as reinforcement bar with the main criteria being strength depending on concrete member function in the structure, and will have superior ductility at low service temperatures.

Design of structural stainless steel components is done to AS/NZS 4673 (Standards NZ 2001), with additional guidance available through Rasmussen (2002).

Grade Selection and Surface Finish

Selection of the correct grade and specification of the correct surface finish are both important factors that greatly affect the long term low maintenance and aesthetic performance of the chosen stainless steel. Basically, the smoother the surface finish the better the corrosion resistance will be, since a rough surface will retain contaminants, such as chloride ions, which in turn causes pitting and surface rust to form, commonly known as “tea staining” (Figure 11). Tea staining can be minimised or even eliminated by specifying a more corrosion resistant grade and the smoothest surface finish possible, in addition to regular washing of the surface. Note that tea staining is a cosmetic issue and rarely reduces the strength of the stainless steel component.



Figure 11: Example of tea staining.

Regarding the grade selection, different grades have different pitting corrosion resistance. In simple corrosion resistance terms, the duplex grades are better than the austenitic, while the super duplex are better than the duplex. However, there are new super austenitic stainless steels that have comparable corrosion resistance to duplex and super duplex. Therefore it is important that the designer specifies the correct grade for the intended function of the member, taking all the different design variables into account. For example, some austenitic grades (including Grade 316) are susceptible to stress corrosion cracking when exposed to tensile stresses in a salty environment, especially at elevated temperatures. Therefore, the selection of a higher grade, such as a duplex 2205, should be considered since it has higher resistance to stress corrosion cracking.

Common surface finishes start are No 1 (rough dull surface), No 2B (smooth and bright), No 4 (satin) to Number 8 (mirror finish), with different finishes in between. Therefore, a No 1 finish has a higher corrosion rate than a No 8 finish, which has the lowest corrosion rate. Further guidance on prevention of tea staining is available from the Technical FAQ No 6 (ASSDA 2010) where a surface roughness of less than 0.3 microns is recommended.

It should be noted that for reinforcement bars, the surface finish is not an issue as being embedded in concrete provides additional protection in comparison to members fabricated from plate and exposed to atmospheric conditions.

Durability Design

The best solution in minimising future durability problems is to design the problem out during the initial stage of the project. Issues, such as crevice, pitting and dissimilar metal/galvanic corrosion, affect all metals, whether they are coated carbon steel, weathering steel or stainless steel. Guidance on these issues is given in different publications such as Design Manual for Structural Stainless Steel (SCI 2006) and on Technical FAQ No 1 (ASSDA 2009).

Most of these issues are related to poor detailing and in most cases the issue can be “designed out” during the detailed design of the bridge. Therefore, a relatively small additional time cost during the design stage, could potentially save hundreds of thousands or even millions of dollars in future repair and maintenance.

Fabrication

Fabrication of stainless steel components is similar, but not identical, for those using carbon steel. Tools used in cutting, bending, grinding, drilling holes, and even hammers should be designated to be used on stainless steel only, to minimise iron contaminating the stainless surface. This is when iron particles are

embedded on the stainless steel surface thereby causing localised galvanic corrosion.

For welding, care is required to use the correct welding consumables following the guidance given in AS/NZS 1554.6 (Standards NZ 2012). Heat tint from welding should be removed by pickling, while different post-fabrication cleaning treatments can be used to achieve the required finish and look. This could range from polishing using abrasive discs or flapper wheels to electro polishing.

Transportation, Storage and Erection

Care should be exercised during the handling, storage and transportation of stainless steel, especially for fabricated components that have been electro polished. This is required to prevent iron contamination and damage to the polished surfaces.

Maintenance

The simplest maintenance method for all steelwork, from carbon steel to stainless steel, is regular washing using low pressure water pressure. This will assist in the removal of any contaminate, such as salt, on the surface which in turn could cause durability issues later on. Low water pressure is needed to minimise the likelihood of contaminants being forced into crevices, especially around bolted connections potentially causing crevice corrosion. This is especially important for steelwork in coastal areas, with the regular removal of salt build up will assist in extending the life of the bridge structure.

In the case of stainless steel, a properly designed, detailed, fabricated and erected stainless steel component with regular washing and inspection, will achieve the required performance and design life of the bridge structure.

Current Limitations

It should be noted, that in New Zealand at this time, there could be a limitation in the fabrication capability of large stainless steel components. Capabilities on the use of stainless steel reinforcement bar, decking and fabrication of relatively small structural components are readily available. However, larger fabricated beams or girders will either have to come from overseas or a local fabricator will need to be specially set up for the specific project. Therefore, at this stage the selective use of stainless steel is recommended, unless consultation with the stainless steel supplier and local fabricators at the early design stage was able to confirm the feasibility of large scale fabrication and construction of stainless steel bridge super structures.

The other issue is availability of the required stainless steel grade to the size and finish. Consultation in the early design stage with stainless steel suppliers is required to ensure the material availability and its prompt delivery to meet the project time line, thereby minimising risk and preventable delay costs to the project.

Conclusions

Stainless steel structural members and components in road, rail and footbridges should be considered in New Zealand, to complement or replace conventional structural materials, such as concrete and carbon steel.

Stainless steels provide a long term cost effective option with minimal maintenance throughout the design life of the structure, with the potential of extending that design life beyond the current 100 year requirement. However, to achieve the maximum potential of stainless steel, the appropriate grade selection, design, detailing, fabrication, erection and maintenance must be carefully undertaken. Existing design guides and standards, both international and New Zealand are available that will assist the designer in achieving the required performance. A number of key design and construction items for the designer's consideration are summarised.

Two costing models, the commonly used net present value method in New Zealand and the more comprehensive life cycle costing model are available to assist in determining the total life cycle cost of the structure. This takes into account the initial construction cost and future expected maintenance for the former model, while the latter also takes into account the loss of production costs during down time and the replacement cost of the structure. It should be noted that stainless steel provides the most economical solution in very corrosive atmospheric environments, whether marine or industrial. For bridges outside these environments, other structural materials may prove to be more economical due to the longer expected time to first maintenance. Selective use of stainless steel components is possible, which will assist in reducing the initial construction cost by optimising use of these different structural materials. Therefore, either costing model should be used at the early design stage to assist in the selection of the most cost effective long term solution.

Finally, while stainless steel has many benefits, in New Zealand at this stage, there is a limited fabrication capability for the construction of large stainless bridge components. Capabilities in the use of stainless steel reinforcement bar, decking and fabrication of relatively small structural components are readily available. Therefore, at present the selective use of stainless steel is recommended, unless consultation with the stainless steel supplier and local fabricators at the early design stage is able to confirm the feasibility of large scale fabrication. Consultants should also confirm the availability of the required stainless steel grade in the size and surface finish to ensure its prompt delivery to meet the project time line, thereby minimising risk and preventable time costs to the project.

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