HERA Design Guide
for Bridges in Australia

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Weathering Steel

Design Guide for Bridges in Australia

BLUESCOPE

Commissioned by BlueScope Steel Ltd

Weathering Steel
Design Guide for Bridges in Australia

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Contents

1. Introduction

Weathering steel is a high strength, structural steel that, in suitable environments, develops a tightly adherent oxide layer or 'patina', which significantly reduces the corrosion rate compared with conventional structural steel.

Weathering steel has been used since the 1930's in railway coal wagons, bridges, buildings, facades and many architectural features such as sculptures and landscaping. It has been used extensively in North America, Europe and Japan for over 55 years; and over the last 10 years in New Zealand. When designed and detailed correctly, taking into account the environmental factors that governs its use, it has exhibited excellent performance.

A well designed and correctly detailed weathering steel bridge, in an appropriate environment, can provide an attractive, very low maintenance, economic solution and extends the scope for cost-effective steel bridges.

Accordingly, the Heavy Engineering and Research Association of NZ and Opus International Consultants, NZ have prepared this document entitled 'Weathering Steel Design Guide for Bridges in Australia'. The purpose of this publication is to provide a collation of the necessary guidance for the Australian industry to assist with the efficient and appropriate application of weathering steels in Australian bridges. It also provides guidance to achieve the expected performance of weathering steel in Australian bridges, to realise the planned life span of the bridges.

This publication covers the designing, construction, inspection, maintenance and even rehabilitation of weathering steel, should corrosion rates exceed those anticipated at the design stage, as well as discussing the limitations on the use of weathering steel.

Comments and queries on the guide should be referred to HERA.

2. Background to Weathering Steel

2.1 What is Weathering Steel?

Weathering steel, or to use its technical title of "structural steel with improved atmospheric corrosion resistance", is a high strength low alloy structural steel that, in suitable environments, may be left uncoated because it forms an adherent protective rust "patina" that minimises further corrosion. The alloys added to weathering steel compose only 2% of the steel make-up with specific alloying elements such as copper, chromium, silicon and in some cases phosphorus. The additional alloying does not diminish the structural capability of the steel, with the steel offering strength, ductility, toughness and weldability suitable for bridge construction and covered by the Australian Standard AS/NZS 3678.

All structural steel corrodes, at a rate which is governed by the access of moisture and oxygen to the metallic iron. As this process continues, the oxide (rust) layer becomes a barrier restricting further ingress of moisture and oxygen to the metal, and the rate of corrosion slows down.

The rust layers formed on most conventional carbon-manganese structural steels detaches from the metal surface after a period of time and the corrosion cycle commences again. Hence, the corrosion rate progresses as a series of incremental curves approximating to a straight line, the slope of which depends on the aggressiveness of the environment.

The weathering steel rust patina is initiated in the same way but, due to the alloying elements in the steel, it produces a stable corrosion nano-layer (Kimura 2005) that adheres to the base metal and is much less porous. This layer develops under conditions of alternate wetting and drying to produce a protective barrier which impedes further access of oxygen and moisture. Eventually, if this barrier is sufficiently impervious and tightly adhering, the corrosion rate will be greatly reduced. The resulting reduction in corrosion rates is illustrated in Figure 2.1.

In a suitable environment this stable condition may be reached within 8 years, or more, depending on the local environmental factors. At this stage the metal is then protected from significant future corrosion by the rust patina. Assuming that there is no significant change in the environment, and with regular inspection to determine and treat any isolated problem areas if they occur, the potential life of a weathering steel bridge is expected to be more than 100 years.

2.2 Benefits of Weathering Steel

2.2.1 Cost Benefit

Depending on the market price of weathering steel, it may be greater than carbon steels; however cost savings from the elimination of the protective coating system typically outweigh the additional material costs. The total life cycle cost of a weathering steel bridge could be up to 30% lower than a conventional coated steel alternative (El Sarraf & Mandeno 2010). In most cases, a weathering steel solution is cost-competitive with an optimised coated steel alternative for most inland environments.

2.2.2 Reduced Construction Time

The total construction period is reduced as both shop and site painting operations are eliminated, to the advantage of the contractor and ultimately the client.

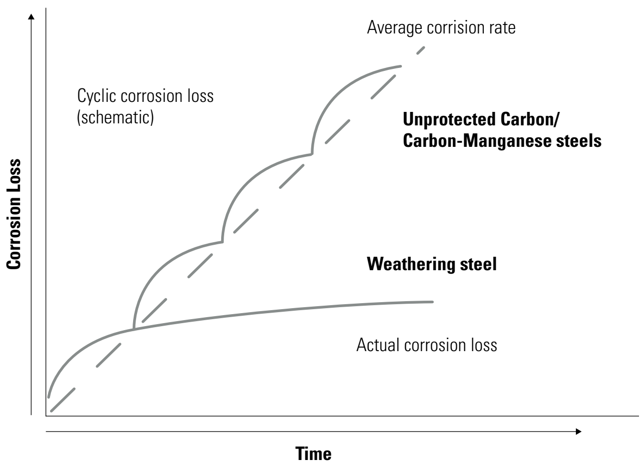
2.2.3 Reduced Cost and Time of Maintenance

If correctly detailed, periodic inspection and cleaning should be the only maintenance required to ensure the bridge continues to perform satisfactorily. Since a protective coating is not normally required, the cost of inspection, cleaning and, in some cases, the occasional remedial treatment of limited areas is usually considerably lower than the costs of regular maintenance and recoating of a fully coated structure. This greatly reduces indirect costs such as those resulting from traffic management and traffic delay, caused by providing site access while coating maintenance activities are carried out.

2.2.4 Environmental Benefits

Coating application and maintenance requires suitable health and safety protection for the applicators and can also require special

Figure 2.1 Schematic comparison between the corrosion loss of weathering and carbon steel



environmental considerations, such as containment of abrasive blast cleaning residue. Hence, the omission of a protective coating by using weathering steel, yields both health and environmental benefits.

2.2.5 Attractive Appearance

The protective mechanism of weathering steel in bridges is the formation of a stable film of a rust patina. Once fully formed and weathered, the appearance of this film is uniform, usually of a dark brown or purple colour. This colour can blend nicely with the environment and improves with age.

2.2.6 Safety Benefits

Health and safety issues relating to initial and subsequent coatings are avoided, and safety issues associated with maintenance access are reduced, thus implementing Safety in Design principles. For example the need to access the confined space inside closed box girders is minimised.

2.3 Where to use Weathering Steel?

As with other forms of construction materials, there are certain environments which can lead to durability problems. The performance of weathering steel in these environments may not be satisfactory and its use in these environments should be avoided.

2.3.1 Marine Environment

Exposure to high concentrations of de-passivating chloride ions will greatly affect the patina formation. These can be deposited from airborne marine salts in aerosol originating from breaking waves at sea or on the shoreline, or from salt fogs, will greatly affect the patina formation. The hygroscopic nature of salt can prevent sheltered surfaces from fully drying when relative humidity is elevated and thus stop the formation of the rust patina, thereby resulting in the weathering steel continuing to corrode at a rate similar to mild steel.

Evidence of a higher corrosion rate and a delayed, or even no, formation of the protective patina has been identified for unwashed and sheltered surfaces (i.e. microclimate effects), as well as in crevices, on weathering steel structures in coastal locations (Morcillo 2013).

Therefore, when determining the suitability of using weathering steel in a given location, the atmospheric corrosivity assessment needs to take into account both the macroclimate, in accordance with AS 4312 and/or the CSIRO Corrosion Mapping and Model (Trinidad 2011); as well as the microclimate effects, as described in the *Australian Steelwork Corrosion and Coatings Guide* (ASCCG) (Clifton et al 2013).

Details regarding humidity levels, wind strengths and wind directions, which assist in determining the macroclimate and microclimate for a specific location, can be obtained from the Australian Bureau of Meteorology site under climate data.

Based on the findings of the Morcillo review of weathering steel performance data, it is recommended that weathering steel should only be used in areas where the maximum first year corrosion rate (taking into account both the macroclimate and microclimate effects on sheltered surfaces) of mild steel is less than 50 μm/yr. This is equivalent to a rain washed surface in atmospheric corrosivity category C3 (Medium) to ISO 9223. Therefore, if the determined atmospheric corrosivity is C4 (High) or C5 (Very High), weathering steel should not be used.

Generally, weathering steel can be used in locations that are more than 2km from the open seacoast, where the maximum first year corrosion rate (taking into account both the macroclimate and microclimate effects on sheltered surfaces) of mild steel is less than 50 μm/yr. However, in some cases, this minimum safe distance may increase up to 40km, depending on prevailing wind strength and direction, ocean wave and coastal surf conditions, topography, obstructions to wind flow and the level of shelter near the site.

Table 2.1 Atmospheric corrosivity categories to AS 4312 and AS/NZS 2312 and description of typical environments

Corrosivity Categories	Description	Corrosion Rate for Steel (μm/year)	Typical Exterior Environment
C1	Very Low	<1.3	Alpine Areas
C2	Low	1.3 to 25	Rural/urban
C3	Medium	25 to 50	Coastal
C4	High	50 to 80	Sea-shore (calm)
C5	Very High	80 to 200	Sea-shore (surf)/offshore

Hence, confirmation of the site atmospheric corrosivity category to assess the suitability of the site is required. See Appendix A for worked examples on determining the atmospheric corrosivity category, using the guidance given in the ASCCG (Clifton et al 2013).

In the case that weathering steel is being considered for sites where the microclimate corrosivity is borderline high C3 (Medium)/ low C4 (High), or less than 2km from the open seacoast; then determination of the actual site-specific corrosivity environment (including those of unwashed and sheltered surfaces), with a minimum of 1 year record, is required. This assessment should be undertaken by an experienced corrosion engineer, having the minimum qualifications given in Section 3.12. It is recommended that the 'coupon weight-loss' technique be used to determine the site-specific corrosivity, rather than testing for salt and sulphur dioxide levels in the atmosphere. Guidance is available for conducting the 'coupon weight – loss' test.

For marine locations near closed bays and sheltered harbours, where C4/C5 environments do not exist and C3 regions can be relatively narrow (< 2km), weathering steels may be able to be used closer than 2km from salt water; the minimum distance being site specific. Site testing of corrosion rates for sites where AS 4312 does not provide guidance for the corrosion category of the location, should be conducted as per the guidance given above.

2.3.2 Localised Adverse Conditions
Contaminated sprays from roads under wide bridges create "tunnel-like" conditions that should be accounted for when the headroom is less than 5.3m.

"Tunnel-like" conditions are produced by a combination of a narrow depressed road with minimum shoulders between vertical retaining walls, and a wide bridge with minimum headroom and full height abutments. Such situations may be encountered at urban/suburban grade separations. The extreme geometry prevents roadway spray from being dissipated by air currents, and it can lead to excessive contaminated spray on the bridge girders.

Leaking expansion joints can be caused by faulty seals exposing bridge members to contaminated runoff water; resulting in a higher time of wetness and increases the risk to the continued corrosion of the weathering steel surface.

Section 3.8 covers detailing solutions to avoid localised durability issues.

De-icing salts used on roads both over and under weathering steel bridges may also lead to problems. These includes leaking expansion joints where salt laden run-off flows directly over the steel and salt spray from roads where "tunnel-like" conditions are created. Both of these cases are much less of an issue in Australia than they are in countries, where sodium chloride based de-icing salts are used on roads, to make driving safer in winter months.

2.3.3 Continuously Wet / Damp Conditions
Alternate wet/dry cycles are required for an adherent patina to form. Where this cannot occur, due to excessively damp conditions, a corrosion rate similar to that of conventional carbon-manganese steel may be expected. Such conditions are to be avoided.

This means that, in addition to the marine environment guidance given in Section 2.3.1, weathering steel members must not be immersed in water, be in contact with soil or be covered by vegetation. There must also be a minimum headroom of 2.5m for crossing over water not subject to significant wave action.

Overseas practice is to limit weathering steel use to regions where the 'time of wetness' is < 60% of the total time. ('Time of wetness' for weathering steel applicability is defined by ISO 9223 as when the relative humidity exceeds 80% at the site). This is based on the classification of times of wetness greater than 60% as being "very damp for corrosion purposes" by ISO 9223 (Category T_5 to ISO 9223). Hence, the humidity level at the site should be less than 80% for more than 40% of the year.

Where the average time of wetness is greater than 60% and up to 70%, the following additional restrictions apply:

– the bridge must not be shaded from sunlight between the hours of 9am to 3pm by permanent obstructions such as surrounding hills, at any time of the year.

– the bridge must be located so there is unobstructed airflow past the steelwork.

– the surrounds must be constructed so there is no vegetation taller than grass within 3 metres of the bridge steelwork.

2.3.4 Atmospheric Pollution
Weathering steel should not be used in atmospheres where high concentrations of corrosive chemicals or industrial fumes, specifically SO_2, are present. Such environments with a pollution classification above P^3 (SO_2 > 250µg/m^3 concentration or 200mg/m2/day deposition rate) to ISO 9223, rule out the use of weathering steels.

In Australia, this level of SO_2 may occur within the vicinity of large industrial sites such as at Mt Isa in Queensland and Port Pirie in South Australia.

3. Design and Detailing

3.1 Design Codes

In Australia, the design for weathering steel bridges should be undertaken in accordance to the relevant parts of Australian Standard AS 5100, especially Part 6.

However, there are a number of requirements, mostly related to detailing and suitability of environment, which relate specifically to weathering steel. These are outlined below.

3.2 Material Specification

BlueScope supplies REDCOR™ weathering steel[1] to the Australian Standard AS/NZS 3678, with the typical material properties given in Table 3.1.

3.3 Allowance for Loss of Thickness

Assuming that the protective rust patina is formed, even with the reduced corrosion rate, an allowance for the expected section loss over the design life of the bridge should be considered. The corrosion allowance is added to each exposed surface and this added thickness for the corrosion allowance cannot be used in the calculation of the structural capacity of the member.

Table 3.2 outlines the corresponding corrosion allowance for a bridge design life of 100 years, as specified in AS 5100.6.

Table 3.1 Properties of AS/NZS 3678 weathering steel

Steel Grade[1]	Thickness of material (t) (mm)	Minimum Yield Stress (MPa)	Minimum Tensile Strength (MPa)	Charpy Impact toughness[2]
WR350	6 to 80[3]	340	450	–
WR350L0				27 Joules @ 0°C
WR350L20				27 Joules @ -20°C

Notes to Table 3.1
1 The Australian steel grade designations mean:
WR: represents "weather-resistant" (i.e. improved atmospheric corrosion resistance or weathering steel).
– 350: represents the Nominal Yield Strength.
– L0: relates to the impact test temperature (0°C).
– L20: relates to the impact test temperature (-20°C).
More detail is found in the Australian Standard AS/NZ 3678.
2 Using Charpy 2mm V-notch impact test specimens.
3 Thicknesses down to 3mm are available as coil plate to AS 1594.

Table 3.2 Corrosion allowance (use with Table 2.1 on page 4)

Atmospheric corrosion classification (ISO 9223)	Weathering steel environmental classification	Corrosion allowance (mm/exposed face)
C1, C2	Mild	1.0
C3	Medium	1.5
C1, internal	Interior (Box girders)	0.5

Notes to Table 3.2
- No allowance required for interior faces of hermetically hollow sections.
- Internals of box (tub) girders supporting concrete decks should be classified as C2, unless designed to prevent water ingress.
- Allowances to apply to all fillet and partial penetration butt welds.
- No allowance is normally made for weathering steel HSFG bolts. See Section 3.5.4.
- Allowances apply to all other structural elements, including stiffeners and bracing etc.
- Weathering steel should not be used for Classifications C4 and C5 or for certain Classification C3 sites as per the guidance given in Section 2.3.1.
- If required, additional guidance on the corrosion allowance can be sought by contacting HERA.

1 For any information on BlueScope REDCOR™ weathering steel visit steel.com.au or call 1800 800 799

3.4 Design

3.4.1 Global Analysis

Since the global analysis for member actions and deflections is usually not particularly sensitive to the exact thickness of the steel sections. The given member sectional area and second moment of area, may be used.

3.4.2 Detailed Design

Although it is unlikely that, at any given section and time during the life of the bridge, that the entire exposed perimeter is uniformly corroded, to the corrosion allowance given above; the members net thickness and area, taking into the account the corrosion allowance, should be used when designing the members structural capacity.

3.5 Bolted Connections

For bolted connections, the following topics should be considered.

3.5.1 Material Selection

The standard bolts used in bridges, are usually Property Class 8.8 structural bolts to AS/NZS 1252, which are supplied as hot-dip galvanized. While, these can be used in weathering steel bridges, the dissimilar metals in contact with each other (i.e. zinc and weathering steel), will result in the depletion of the zinc and corrosion of the bolt over time. Furthermore, they will look distinctly different, especially if the galvanized bolts are coated a dissimilar colour to the weathering steel. This in turn will introduce a maintenance issue, due to the need to refurbish the coating on the bolts over the design life of the structure.

Another unsuitable option are unprotected "black" bolts, with those manufactured to AS/NZS 1111, which are of lower strength, being Property Class 4.6-mild steel. However steel shear studs that are embedded in concrete are acceptable as the alkaline environment prevents galvanic action from occurring.

Instead, weathering grade high strength friction group (HSFG) bolts, nuts and washers should be used. These are available from the United States, Japan or Britain.

Two strengths are available; these are ASTM A325, Type 3 or ASTM A490, Type 3 bolts. In Australian terminology, the ASTM A325 bolt is equivalent to Property Class 8.8 bolt and the ASTM A490 has a higher strength, with mechanical properties of a Properly Class 10.9 bolt. They must be used in conjunction with the matching higher grade nuts and washers

They are available from Britain in metric sizes (such as ASTM A325M) and come as M20, M24 and M30, or more commonly available from the United States in imperial sizes with the [following details:]

3.5.2 Coefficient of Friction

It has been found (Kulak et al, 2001) that for tightly adherent mill scale on the surface of weathering steel at a bolted connection, the connection slips into bearing at a lower shear stress than that of carbon steel with mill scale. The coefficient of friction was $\mu_s = 0.2$ for weathering steel versus 0.35 for carbon steel.

However, for high friction grip connections, the full removal of the mill scale is required, to achieve a higher coefficient of friction of $\mu_s = 0.5$. Therefore to use this higher friction factor, all faying surfaces should be abrasive blast cleaned using non-metallic grit to Commercial Blast Cleaning as defined under the visual cleanliness standard SSPC SP-6/NACE No 3, which is similar to Sa 2 to AS/NZS 2312.1:2014. See Section 4.4 for further guidance on surface preparation.

Furthermore, the development of an adherent rust film, such as that produced by wetting and drying for several months by exposure to rain or washing with potable water, does not degrade the coefficient of friction. However loose rust or any residual mill scale would impair the performance of the joint, and its removal from plies by wire brushing or scraping prior to assembly of the connection must be specified.

Table 3.3

ASTM Designation No.	Size Range inclusive, in	Minimum Proof Stress[1], kpsi	Minimum Tensile Strength, kpsi	Minimum Yield Stress, kpsi
A325, Type 3	0.5-1.0 (12.7-25.4mm), 1.125-1.625 (28.58-41.3mm)	85 (586 MPa), 76 (524 MPa)	120 (827 MPa), 107 (738 MPa)	92 (634 MPa), 83 (572 MPa)
A490, Type 3	0.5-1.5 (12.7-38.1mm)	120 (827 MPa)	150 (1034 MPa)	130 (896 MPa)

Notes to Table 3.3

1 The minimum proof stress is the minimum stress in the installed bolt when installed in accordance with ASTM A325 (or Clause H2.5.2 of AS 5100.6).

3.5.3 Crevice Corrosion and Bolts Spacing

Crevice corrosion is an issue with all types of bolted connections, but provided the surfaces are held together in sufficiently close contact it has been found (ECCS, 2001), that problems such as rust staining and pack rust do not arise.

However, it must be recognised that any flexing in service of the connected steel members can open up the joint and lead to the ingress of moisture and dissolved contaminants as a result of capillary action. Hence more stringent requirements on bolt centres and edge distances are required in comparison to joints in a conventional steel bridge.

– Bolt spacing in lines adjacent to plate/section edges should not exceed fourteen (14) times the thickness of the thinnest component, and in any event should not exceed 175mm.

– The distance from the centre of any bolt to the nearest free edge of a plate should not exceed eight (8) times the thinnest component and in any event should not exceed 125mm.

– These requirements given in (SCI 2015) are slightly more stringent than the requirements give in Clause 12.5.2.3 and 12.5.2.4 of AS 5100.6. If these limitations cannot for any reason be met, either the joint must be protected by a suitable coating or a suitable sealant should be applied around the edge of the joint. Also load indicating and spring washers should not be used.

Designers should be aware of Issue 94 of "Construction and Technology", April 2002, which covers an example of a bridge mounted sign failure between the mounting plate and the bridge beam in weathering steel bridges. It gives recommendations for bolts and treatment of the contact surface between the plate and beam, for attachments to the beams, such as for these signs. See Section 7.2 for guidance on sealing of crevices.

3.5.4 Corrosion Allowance for Bolts

There are no specific code requirements for any allowance to be made on the size of bolts. It is reasonable to assume that in a properly detailed bolted connection (see below), the bolt shank may be treated as "not exposed" and hence no allowance need to be made; the size of the bolt heads and nuts are generally sufficient to accommodate any loss that occurs. If there is any cause for concern (for example poor fit-up or flexible cover plates allowing water to be attracted by capillary action under the bolt head or the nut), local sealing and/or coating is likely to be preferred treatment, since continued wetness could cause corrosion far in excess of any nominal allowance. Maximum bolt pitches to avoid capillary action occurring are given above.

3.5.5 Design of Bolted Connections

As previously discussed, while metric sized weathering steel bolts are available, imperial sized bolts are more commonly used. As such, it is recommended that bolted connections are designed for the M24 bolt, but with 1" bolt spacing. This will maximise the procurement options available to the contractor, who can then substitute 1" bolts for M24 bolts, without affecting the layout or design of the connection.

Alternatively, if it was confirmed from the beginning of the design process that imperial bolts will be used, it will more economical to design for the larger 1" bolts, due to the additional available capacity in comparison to the slightly slimmer M24 bolts.

Bolts in tension friction and bearing-type connections of weathering steel bridges should be tightened using the part-turn method as outlined in Clause H2.5.2 of AS 5100.6 and spaced as detailed in Section 2.9.

As discussed, great care also has to be taken to avoid crevices which can admit water at the ends of lapping plates, and similar details. While the designer can specify joints such that this is unlikely, the fabricator still has to ensure good fit-up with flat plates. As a last resort, sealants are available which will perform adequately with weathering steels to prevent water ingress to such joints.

3.6 Welded Connections

Welding is of critical importance in the fabrication of steel structures as welds are usually the most critical parts of the structure. Therefore great attention should be given to the selection of welding consumables to achieve the desired characteristics of resistance to atmospheric corrosion and colouring pattern of the welds; especially when a client has particular expectations for the appearance of a fabrication. Welding must comply with the quality requirements of the applicable welding standard and product specifications. In Australia and New Zealand welding of weathering steels is required to comply with AS/NZS 1554 Part 1 or 5. All joints, including fillet welds, should be continuously welded to avoid moisture and corrosion traps such as crevices.

Site welding should be generally avoided as it requires local grit blasting or grinding after welding which may lead to differences in appearance of the welded joint from the rest of the steelwork. If site welding is to be used, this must be designed and detailed for from the start of the design stage and preferably not made as a late change in the design and detailing process, once the general details and layout are established.

A prerequisite for obtaining identical mechanical properties in the weld and in the base material is the use of suitable welding consumables and the choice of appropriate welding conditions accordingly to AS/NZS 1554. The Standard however does not specify requirements for every aspect of the welding; there are various matters that need to be resolved between the designer and the fabricator. This includes the possible use of C-Mn unalloyed welding consumables for single run welds and type and amount of welding inspection. Appendix D in AS/NZS 1554.1 provides the list of "Matters for resolution"; a normative part of the Standard that both designers and fabricators must consider before the start of the job.

BlueScope also have an advisory Technical Note on the Welding of Weathering steel (Supplement to Technical Bulletin TB 26) that provides guidance on the welding of weathering steels.[2]

See also Section 4.3 and note to Table 3.2.

3.7 Fatigue

Concern has been expressed that weathering steel bridges may exhibit lower fatigue performance than those in ordinary structural steel. This view comes from the fact that corrosion forms pits from which fatigue cracks might initiate easily, with the corrosion then following the crack and hence increasing the speed of propagation. Many tests have been carried out worldwide to investigate this, and whilst the results are not all in full agreement, there seems to be a general consensus that:

(a) After the weathering process has occurred, parent weathering steel (e.g. constructional details 1-3 from Table 13.5.1(A) of AS 5100.6), will have lower fatigue strength than parent non-corroded steel, because of the greater surface roughness under the corrosion layer.

(b) Fatigue failures in bridges are almost always initiated at a point of geometrical discontinuity or stress concentration such as a weld: this gives a much greater reduction below the parent steel fatigue strength than does the presence of corrosion pits in weathering steel. It appears that, provided the detail category to Table 13.5.1(A) of AS 5100.6 of the critical detail is 100 or lower, the use of weathering steel will not cause any reduction of fatigue life. Even if the detail is detail category 112, degradation would be minimal.

(c) Tests which show worse behaviour of joints with low fatigue detail category in weathering steel have apparently always been carried out in very adverse testing environments (for example continuously sprayed with salt water). Weathering steel should not be used for bridges in such environments. Therefore, provided that the guidelines on suitable environments given in Section 2.3 are observed, the results of such tests will not be applicable.

Even though in practice welded weathering steel bridges will not have a lesser fatigue performance than those of coated steelwork, it is necessary to design the details to be as fatigue-resistant as practicable. As is discussed in Section 5.6, fatigue cracks in weathering steel bridges are much harder to detect than those in coated carbon steel bridges.

Figure 3.1
Grinding flush of welds which otherwise form water traps

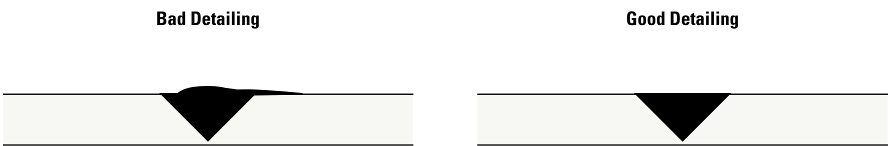
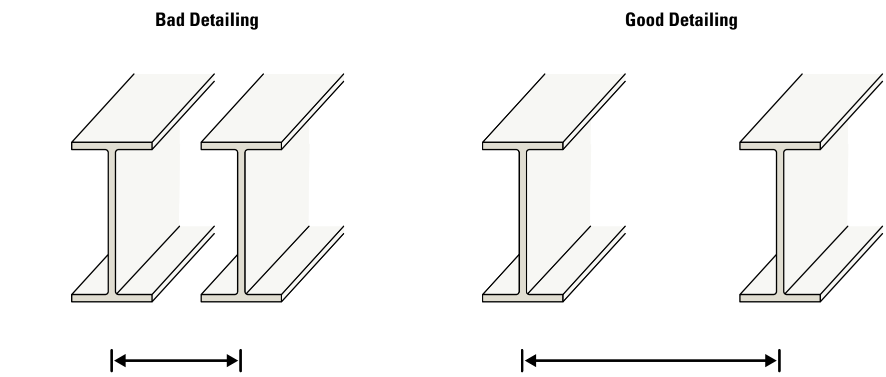


Figure 3.2
Spacing of Girders



2 Technical Note on the Welding of Weathering Steels, BlueScope

3.8 General Structural Detailing

The first principle to be stated when detailing a weathering steel bridge is that good structural detailing practice should be used. In this regard, in the correct environment, a bridge whose details would give no problems in coated carbon steel bridge would behave entirely satisfactorily if designed in weathering steel.

However, the following details are particularly important to be aware of:

3.8.1 Drainage

A weathering steel bridge should not be permanently wet or damp. Hence, even if the general environment is satisfactory, it is important to ensure by good detailing that a high time of wetness does not occur at any point on the bridge steelwork.

There are a number of ways in which this can be achieved, some of which are illustrated below. Some of these details may be expensive to fabricate or, if in fatigue sensitive areas, may lead to a reduced fatigue life. A designer must carefully weigh the relative advantages and disadvantages, taking all factors into account, before selecting a detail.

Weathering steel bridges should be detailed to ensure that all parts of the steelwork can dry out, by avoiding moisture and debris retention and by ensuring adequate ventilation and any ponding of water.

Common practices in this regard are to:

– Grind flush weld details which may cause water traps. (Figure 3.1)

– Provide 50mm copes where stiffeners are attached to the bottom flange.

– Avoid closely spaced girders to aid ventilation. (Figure 3.2). This is also a more economical layout.

– Avoid overlaps, pockets, faying surfaces and crevices, which can collect and retain moisture. (Figure 3.3 to 3.6)

– Hermetically seal hollow sections, or provide adequate access, drainage, and ventilation. (Figure 3.7)

– Provide slopes or cross fall to ensure water runoff. Provide drip plates to direct runoff away from bearings or where staining could occur.

– Where possible web plates of box girders should extend 20mm below the bottom flange. (Figure 3.7)

Figure 3.3
Curtailing transverse web stiffeners to allow drainage below

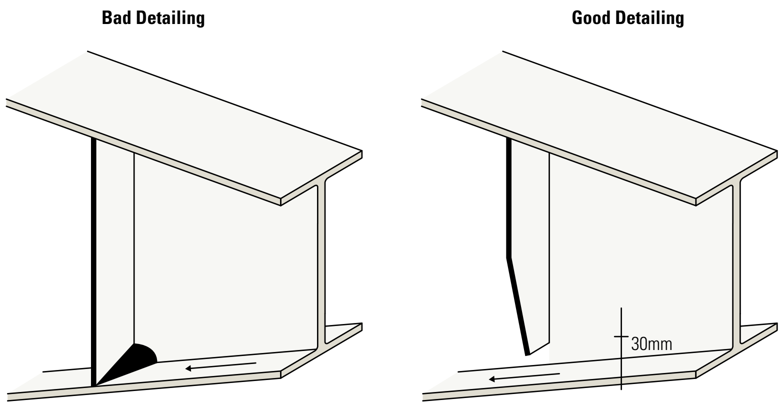


Figure 3.4
Optimum choice of transverse stiffener shape

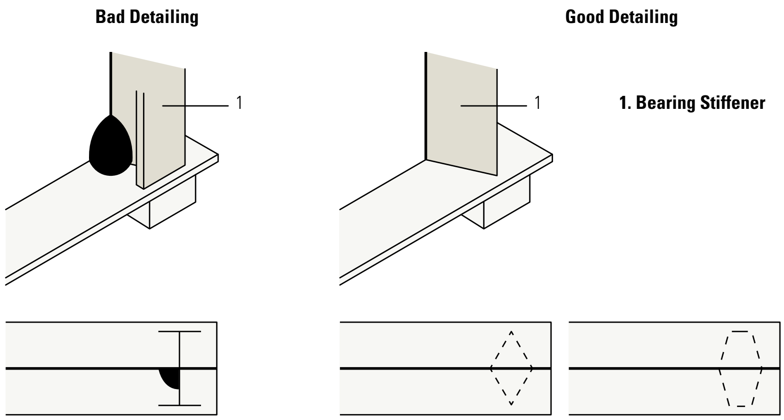


Figure 3.5
Correct orientation of longitudinal stiffeners

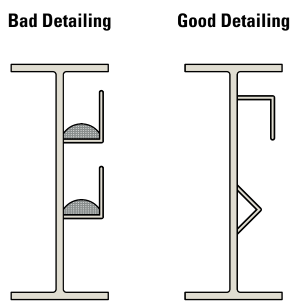


Figure 3.6
Provision of run-off slopes on external flanges

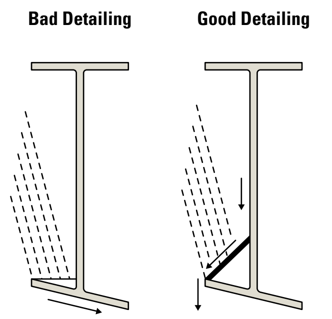
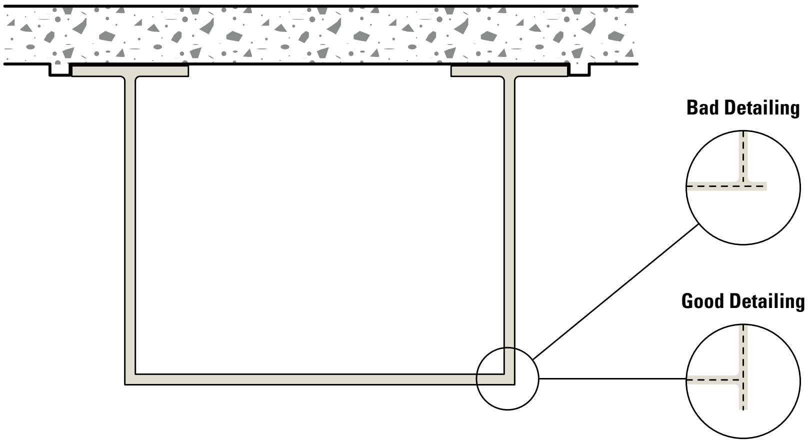


Figure 3.7
Use of Box Sections



Note:
Use box section girders where technically and economically feasible, and ensure that lower flanges do not project horizontally (see Figure 3.5). However internal condensation may occur and adequate internal ventilation and drainage must be provided, especially when supporting an unsealed concrete deck.

3.8.2 Crevices

Crevices should be minimised and where possible, eliminated. Crevices can attract moisture by capillary action, and can be a particular problem for weathering steel bridges, as they are not coated or sealed. Crevices can occur at any point where two surfaces are in contact, and are particularly an issue for bolted connections where plates lap (see further comment on bolted connections in Section 3.5.3, including maximum bolt spacing). If a crevice is not adequately sealed, not only is water attracted into the crevice without much chance of escape, but the corrosion products formed as a consequence have a higher volume than the original material that may result in the distorting or bursting of the connection. Furthermore, the corrosion products themselves will tend to attract further water and thus aggravate the situation.

In cross bracing between girders, use angles “flange upwards” (Figure 3.5; good detailing), and select “K” bracing rather than “X” bracing to avoid crevices at the intersections. If “X” bracing must be used, fill out the intersections with tightly fitting filler plates, (See Figure 3.8).

3.8.3 Expansion Joints

Minimise the number of deck joints, as leaky deck joints are one of the most common causes of problems in weathering steel bridges, allowing contaminated water to drop onto the steel below the deck, as well as increase the time of wetness that will affect the patina formation. Therefore, weathering steel should be used for bridges in conjunction with the deck being continuous over intermediate piers (Figure 3.9) and, where possible, where the deck is integral with the abutments, see (El Sarraf et al 2013) for additional guidance.

Figure 3.9 Long span "jointless" bridge
[image courtesy of the Texas Department of transportation (TxDOT)]

Figure 3.12a Good detailing producing an abutement free of staining
[Image courtesy of www.steelconstruction.info]

Figure 3.12b Bad detailing (severe staining)
[Image courtesy of TxDOT]

If deck joints are unavoidable at abutments, give special attention to them to ensure that they do not leak or, if there is any risk of leakage, that they are provided with a positive drainage system whose outlet pipes are of sufficient length to ensure that the discharge water does not spray on to the adjacent steelwork or substructure in any wind condition. The use of drainage items of a non-metallic type is preferable.

3.8.4 Run-off

Run-off of water from the super-structure and drains should not be permitted to run down the visible external surfaces of the substructure. Until the patina is fully formed, run-off water is liable to contain rust from the weathering process, and unless it is kept away from such surfaces will cause unsightly staining. The drainage of the deck, piers, and abutments requires careful design and detailing to ensure that staining is avoided.

This usually means channelling any run-off water on the tops of piers or abutments, and around bearings to a drain, or drains, feeding into down-pipes which discharge away from the pier or abutment. Particular care should be taken to ensure (by diversion strips or otherwise) that run-off from bottom flanges occurs away from piers. Refer to Figure 3.10 and Figure 3.11 for appropriate drainage in the abutment, and the correct orientation of the drip plate. Also see Figure 3.12 and Figure 3.13 which show examples of good and bad detailing.

Figure 3.8
Cross Bracing Details

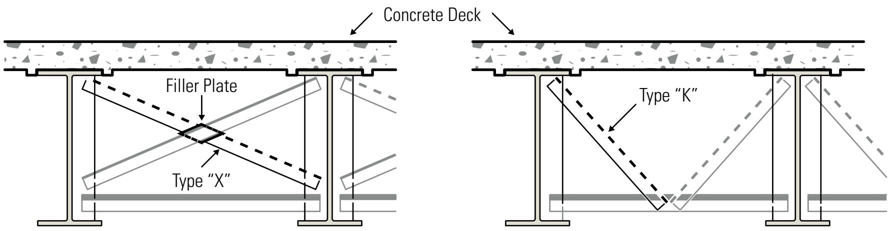
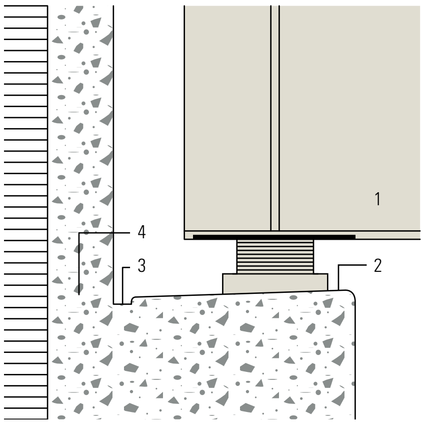


Figure 3.10
Sloped abutment platform and drain



1. Bearing stiffener
2. Sloping top of pier
3. Drainage gutter
4. Drainage pipe
5. Drip plate

Figure 3.11
Drip plate attached to bottom flange, sloped to prevent debris accumulation. Sloped abutment platform and drain

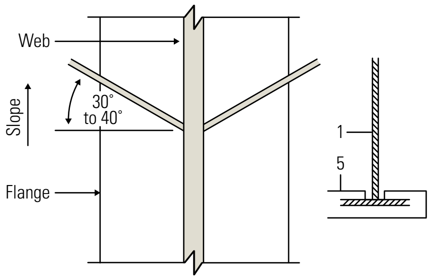


Figure 3.13 Bad detailing of drip plate. Drip plate improperly set at 90°, creating corner for debris accumulation (left); and Drip plate not set at proper angle (right).
[Images courtesy of TxDOT]

Figure 3.14
Well designed drip pan installation

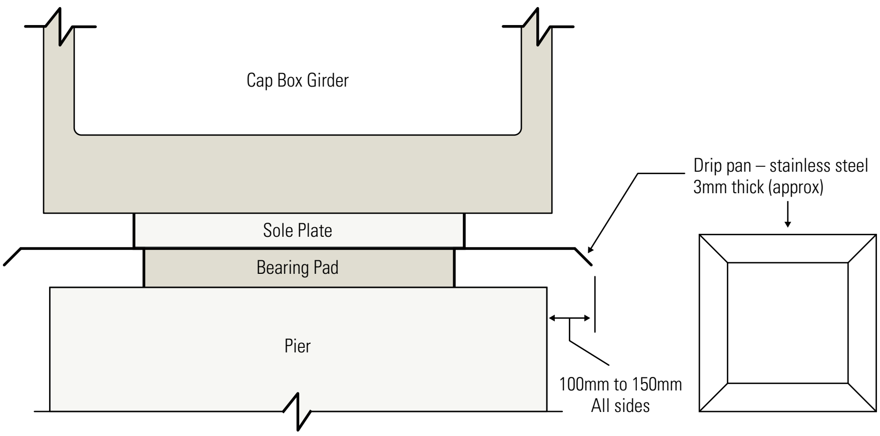


Figure 3.16
Design of retrofitted drip pan

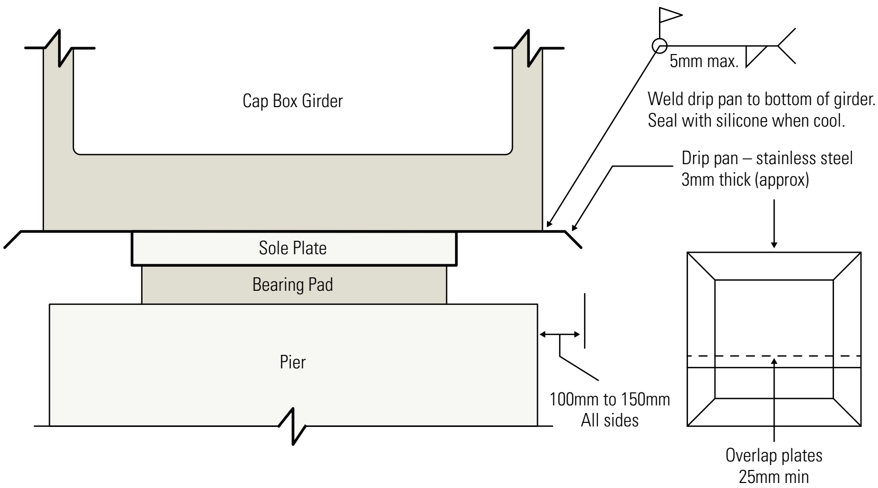


Figure 3.14 shows the design of a drip pan, followed by Figure 3.15 which demonstrates good and bad detailing of the drip plate and drip pan.

Figure 3.16 shows the design of a retro drip pan, followed by Figure 3.17 which demonstrates good and bad detailing of the retrofitted drip pan.

It should always be kept in mind when designing a weathering steel bridge to make it easy to inspect. Inspection is required to ensure that an adherent protective patina has been formed and is not flaking off, that moisture and detritus are not collecting, and that the thickness of the structural elements is as expected by the Bridge Designer at that point in time. A programme of monitoring (in accordance with Section B2.2 of the *Guidelines for Bridge Management* (Austroads 2004) should be specified, and the design must make allowance for this to be done. All parts of the bridge should be designed to be readily accessible for an appropriate level of inspection.

Figure 3.15 Good and bad detailing of a drip plate and drip pan
[Images courtesy of TxDOT]

(a) Concrete column without protection of drip pan

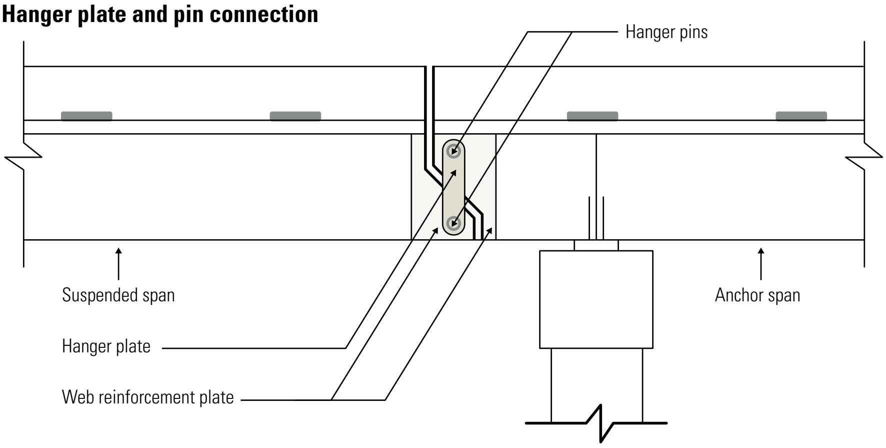
(b) Insufficient drip pan overhang permits run-off to blow onto pier

(c) Stain-free concrete due to installation of drip plate

3.8.5 Hangar Plate and Pin Connection

Hanger plate and pin connections (see Figure 3.18 for details) at cantilever expansion joints of girders are exposed to water leaking through open deck joints. If these details are of weathering steel they can be severely corroded in the gap between the girder web and the hanger plates. Also, there can be some galvanic corrosion of the steel girder with respect to the bronze washer installed between the girder web and the hanger plates. If the corrosive attack is severe, the gap between the girder web and hanger plates becomes tightly filled with rust, and may lead to pack out failure as discussed earlier. These details are bad from a corrosion standpoint even if the joints are painted.

Figure 3.18
Hanger plate and pin connection



3.8.6 Box and Tubular Members

Box and tubular members for welded girders, columns and trusses constructed of weathering steel will corrode on the inside if water is continuously present. This can be prevented by fully sealing the member or ensuring adequate drainage holes are provided. If a pipe carrying water passes through a girder, drain holes should be provided in the bottom of the girder so as to drain water in the event of a leak. Consideration can also be given to insulating the water line to prevent condensation on the pipe exterior. Drain pipes should not pass through box members.

3.8.7 Box Girders

Composite steel-concrete box girders cannot be hermetically sealed, because moisture may come in through cracks in the concrete deck slab. Therefore, provision must be made for drainage of moisture and for adequate ventilation to minimize corrosion of the interior. If the interior is accessible so that periodic corrosion inspections can be made, coating of the interior is unnecessary. However if future interior coating becomes necessary, it would be helpful to inspectors if a white alkyd coating system was used. If interior inspections to monitor condition of unsealed boxes are not possible, coating the interior is recommended.

Alternative steps to coating may be taken to insure satisfactory corrosion performance for the interior of unsealed, composite box girders. These are:

- Waterproof and pave the bridge deck to prevent water from leaking through the deck and into the box girder interior.
- Provide access holes with locked covers on screens to keep out vermin and birds but to allow inspection.
- Ventilate the girder by drilling 50 mm dia holes in the bottom flange at the lowest point of each compartment. Where there is <2 degrees slope to bottom flange provide drainage holes at ~10m centres. Insert a small tube fitted with an insect screen into the hole so that the top of the tube is flush with the top surface of the bottom flange and the tube itself protrudes below the flange.
- Locate the inspection hatches for easy access by the inspector.

Figure 3.17 Good and bad detailing of a retrofit drip pan
[Images courtesy of TxDOT]

(a) Improperly retrofitted drip pan on pier allows staining.

(b) Poor welding on retrofitted drip pan.

(c) Properly retrofitted drip pan on pier.

3.8.8 I-Girders

Corrosion of weathering steel members is most likely to occur on horizontal surfaces, in crevices and re-entrant comers. On I-girder bridges it has been found that locations where corrosion attack is most likely are the top surface of bottom flanges, gusset plates, longitudinal stiffeners, splices of horizontal and sloped members and where flanged gusset plates contact bearing and intermediate stiffeners. Therefore, to reiterate the guidance given above, good design and detailing practice should involve:

- eliminating crevices and minimizing re-entrant comers,
- providing for good drainage at low points when girders slope away from the centre supports and toward the end supports
- changing the flange thickness instead of the width, where welded flange splices are used, because changes in widths may cause uneven water flow.

3.9 Removal of Rust Stains

Although rust staining should not occur on a well detailed weathering steel bridge, it is worth noting that concrete, stone, wood, galvanized steel and unglazed brick are difficult to clean. Hence, it is recommended that substructures are sealed with washable organic coatings to facilitate cleaning with commercial products, should rust staining occur.

The following materials are subject to minimal staining and can generally be cleaned relatively easily:

- Ceramic tile and glazed brick
- Washable air-drying and thermosetting organic coatings
- Stainless steels
- Aluminium, anodised and un-anodised

3.10 Interface Protection

Other issues to consider include:

- Elements buried in soil should be coated, up to 100mm above the ground, with a minimum of 350microns of a suitable barrier coating, such as a high build epoxy or polyurea, to minimise non-atmospheric corrosion and risk of 'ring bark' corrosion.
- Interfaces between steel and concrete should be separated, using a minimum of 150microns of non-conductive barrier coating. See Section 4.13 of (Clifton et al 2013) for further details.
- Elements embedded in concrete need not be coated, except 100mm from and 50mm above the interface. See Section 4.13 of (Clifton et al 2013) for further details.
- Contact between steel and treated timber must be avoided, unless a mastic strip or damp proof course is placed between these components.

3.11 Connection to Other Materials

In general, any connection to a galvanically dissimilar material runs the risk of galvanic corrosion of either the weathering steel or the other material (such as galvanized bolts). However, this will only occur in the presence of water. Therefore for connections between dissimilar metals inside a dry weathering steel box girder, the risk of galvanic corrosion is minimal.

Care should also be used if weathering steel and stainless steel (for example in bearings) are connected without appropriate electrical insulation. In this case the weathering steel would become anodic and corrode preferentially, although experience has shown that provided the joined area does not act as a crevice to attract water; serious problems are unlikely to arise. Such an application is the drip pan detail shown in Figure 3.14. The contact surfaces and regions around them can be coated with a 150 microns of non-conductive barrier coating, as shown in Section 4.13 of (Clifton et al 2013).

3.12 Further Protection – Coating

There are some weathering steel bridges in existence where the designer wished to provide further protection from the outset. Coating the steelwork has been specified in areas where it was thought that the environment would prevent the formation of the protective patina. This can either be due to the accumulation of debris, salt, and/or other contaminant. Such areas include; the top surfaces of bottom flanges, perhaps together with some of the bottom of the web, areas below deck joints and under the ballast in trough section railway bridges.

In such circumstances, coating these potential problem areas should be considered. There is some evidence that, although a barrier coat lasts no longer than on ordinary structural steel, if the coat is damaged or degraded the self-stifling properties of the rust which is formed helps to prevent under-creep. This can be beneficial since damaged areas which require touch-up and recoat will not spread to any extent even after a prolonged period of time.

Implications for the appearance of the bridge should be considered when specifying local coating and the colour of the coating system on exposed steel work should be selected to match the expected colour of the steel. These should be able to be applied on to a high pressure water cleaned surface and should comprise a single coat system where possible. See AS/NZS 2312.1 and (Clifton et al 2013), for guidance on a suitable coating system such as a direct to metal high build water based acrylic elastomer or a high-ratio calcium sulfonate alkyd.

It is recommended that a qualified coating specifier is used to prepare, or review, the refurbishment specification. The required qualification for such a specifier should be one of the following:

- NACE Protective Coating Specialist.
- Australasian Corrosion Association (ACA) Technician or Technologist with successful completion of the ACA's Coating Selection and Specification Course and/or certified to NACE Coating Inspection Program (CIP) Level 2.

Image courtesy of www.steelconstruction.info

4. Fabrication and Construction

4.1 Cold and Hot Forming

As with most high strength structural steels, cold forming is not generally recommended for structural shapes or for plates and bars over approximately 20 mm thick, in accordance with AS 3678. The minimum cold bending radii are given in AS3678 for plate thickness up to 20mm however, note the need to condition the plate edge prior to cold bending. Also, where fracture toughness is important, AS 4100, in the sections on brittle fracture, provides guidance on the effect of cold forming strain levels on the resultant change in notch toughness of structural steels.

Hot forming can affect both the tensile properties and the notch toughness, particularly in steels without sufficient grain refining elements. Even in steels with grain refining elements (including most weathering steels) certain supply conditions (such as thermo-mechanically controlled rolled) may incur a significant loss of strength from hot forming. Steel supplied in the normalised condition may be able to sustain some heat treatment or hot-forming processes, if the steel is heated to the appropriate temperature range. Accordingly a maximum temperature of 600°C is recommended; see Clause G3.1 of AS 5100.6 or contact the steel supplier for guidance.

4.2 Cutting

Flame-cutting (for example oxy-acetylene or oxy-propane) or plasma-arc cutting of weathering steels can be carried out using the same procedures as would be applied to carbon steels of similar carbon equivalent value and thickness. Application of preheat temperatures similar to those used for welding will avoid excessive hardening of the flame-cut edges. If required, grind the hardened edges, as if left, this will affect the formation of the protective patina at that surface.

As general guidance, for a thermally cut edge not subsequently fully incorporated in a weld, cracking is more likely to occur if the hardness exceeds 350 HV (Vickers Pyramid Number).

4.3 Welding

4.3.1 Welding processes

Weathering steel can be is welded using the same techniques used for low alloy steels. Typical welding processes used are submerged arc welding (SAW), flux-cored arc welding (FCAW), gas metal-arc welding (GMAW or MIG) and manual metal-arc welding (MMAW).

4.3.2 Preheat

The welding of structural weathering steels is similar to that of conventional structural steels, but weathering steels generally have higher Carbon Equivalent (CE). Steel grades CW300, HW350 and WR350 have a Weldability Group Number 5 in accordance with the Table 5.3.4(A) of AS/NZS 1554.1. It is based on the typical maximum carbon equivalent encountered in Australia and New Zealand weathering steels, rather than a maximum specification limit normally applied. The preheat temperature should be determined in accordance with Section 5.3 of AS/NZS 1554.1.

4.3.3 Hot cracking

As weathering steels typically contain levels of phosphorus and/or copper significantly higher than that found in C-Mn structural steels, in certain joint configurations and higher heat inputs typically associated with the SAW process, the weld may be at risk of hot cracking; also referred to as solidification cracking. The solidification crack susceptibility of weld metal is affected by both its composition and weld-run geometry (depth/width ratio). The chemical composition of weld metal is determined by the composition of the filler material and the parent metal, and the degree of dilution. The degree of dilution, as well as weld-run geometry, both depend on the joint geometry (angle of bevel, root face and gap) and the welding parameters (current and voltage). At normal heat inputs used in manual or mechanised welding the risk of hot cracking is considered low, however at higher heat inputs, particularly >2.5kJ/mm, and for fillet weld runs having a depth/width ratio greater than 1, the risk of hot cracking is relatively high. If in doubt, a hot cracking test should be considered as part of the weld procedure qualification test requirements to verify freedom from hot cracking. Test methods are provided in AS 2205.9.1.

4.3.4 Selection of welding consumables

Welding small-sized, single-pass welds typically causes a high amount of base metal dilution; a large amount of base metal is melted and mixed with the weld metal. As a result, the weld picks up a sizable amount of alloying elements from the weathering steel, which can provide the weld metal with the same atmospheric corrosion resistant properties as the base metal itself.

C-Mn consumables may be used for single-run fillet welds up to 6 mm leg length and for butt welds made with a single run or a single run each side and where the welds are made with no weave. Refer to BlueScope's Technical Note on 'The Welding of Weathering Steels', Supplement to BlueScope Technical Bulletin Number 26 (TB 26), for more detailed guidance. Weld procedure prequalification is recommended to ensure sufficient dilution of the base plate into the weld metal has been achieved to provide adequate atmospheric corrosion resistance. C-Mn welding consumables to be selected in accordance with Table 4.6.1(A), AS/NZS 1554.1.

Welds on weathering steels may be visible due to the colour contrast between the base material and the weld metal. In some applications it is desirable to have the appearance of the weld seamlessly blended into the base metal. In these cases, the use of welding consumables with similar weather resistance properties in accordance with Table 4.6.1(C), AS/NZS 1554.1 is recommended even for single-run welds.

Large, multi-pass welds typically do not experience a significant amount of base metal dilution. For this reason, carbon steel filler metals cannot pick up enough alloying elements from the base material to provide the necessary atmospheric corrosion resistance. Instead, a low alloy filler metal is recommended to ensure that the weld will have the same corrosion resistance as the weathering steel. For larger single-run fillet welds and butt welds made with a single run or a single run each side and where weaving is used during the run, welding consumables should be selected in accordance with Table 4.6.1(C).

For multi-run fillet welds and butt welds, the main body of the weld can be made using C-Mn electrodes selected to Table 4.6.1(A), AS/NZS 1554.1, capped off with 'matching' electrodes. For capping runs on multi-run fillet or butt welds, the welding consumables are to be selected in accordance with Table 4.6.1(C).

Commonly used low alloy filler metals for weathering steel applications include those with a minimum nominal nickel content of one percent. That alloy content is sufficient to provide atmospheric corrosion resistance similar to the weathering steel, and the cost is typically less than other low alloy filler metals with acceptable properties. Filler metals with a higher nickel content and other alloying elements, can be used in accordance with the Table 4.6.1(C), AS/NZS 1554.1. Weathering steel welding consumables with a higher impact grading are also acceptable.

The American Welding Society's Standard Table 3.3 of AWS D1.1 provides a broader range of consumable options for common welding processes where a matching patina is required on multi-pass welds in particular. Consumables meeting these requirements may be used to weld WR350 and HW350 grades.

Where consumables are not selected in accordance with the above, additional qualification tests may be required to establish suitability for use within the chosen application.

4.3.5 Quality requirements

All welding fabrication including quality of the weld should comply with AS/NZS 1554 Part 1 or Part 5. The fabricator should demonstrate the ability to produce sound welds via a documented weld procedure and welder qualification tests. The fabricators should ensure that all welding and related activities are managed under a suitable quality management system. Such a system should generally comply with the requirements of AS/NZS ISO 3834 part 2 or 3. All welding should be performed under supervision of the welding supervisor as per section 4.12, AS/NZS 1554.1:

4.4 Surface Preparation

Further quality requirements are given in the Australian Standard for Fabrication and Erection Standard for Structural Steelwork, AS/NZS 5131. It is recommended this Australian Standard be consulted for guidance on the welding fabrication of weathering steel.

4.4.1 Mill scale removal

Commercial Blast Cleaning as defined under SSPC SP-6/NACE No 3, which is similar to Sa 2 to AS/NZS 2312.1: remove oil, grease, dirt, rust scale and foreign matter. It also removes most of the mill scale, coating, and rust in the bottom of pits except for slight streaks or discolorations. At least two-thirds of the surface area should be free of visible residues except for the discolorations previously mentioned. The resultant surface will weather relatively uniformly. The process is considerably less expensive than near-white blast cleaning (SSPC-SP10/NACE No 2, similar to Sa 2 ½); however the finished appearance is less uniform.

It is important that all contaminants are removed from the surface of the steel to enable it to form a uniform protective rust patina. Mill scale will be undercut during the weathering process and will fall off eventually, but will also delay the formation of a uniform coloured protective layer; hence it is recommended that mill scale is removed from the whole surface and not just the faying surfaces (Section 3.5.2). As such the following clause should be included in the bridge specification.

After fabrication and prior to erection, all weathering steel components shall be abrasive blast cleaned to SSPC-SP 6/NACE No 3 to remove mill scale and other contaminants. This shall be immediately followed by a minimum of 3 cycles of wetting using potable water and drying, to assist in the formation of the protective patina and provide a uniform finish.

4.4.2 Grinding and Other Cleaning Methods

Prior to abrasive blast cleaning, or if the following contamination was caused during erection, the following surface preparation methods should be undertaken.

- Wax-based crayons should not be used to mark weathering steel. However, if such marks are present, they may be removed by solvent degreasing.
- Oil, grease, and cutting compounds may also be removed by solvent degreasing (AS 1627.1 or SSPC-SP1). Alkaline cleaners or a combination of detergents and steam may also be used. When alkaline cleaners and detergents are used, their use should be followed with high pressure water cleaning to remove any residue.
- Acids should not be used for cleaning because of the possibility of acid residues remaining on the steel surfaces and causing corrosion.
- Localized weld spatter or other welding residues may be removed by power tool cleaning (SSPC-SP15).
- Loose deposits of rust, rust scale, coating or other foreign matter may be removed by hand tool cleaning (St2 or SSPC-SP2) such as scraping or wire brushing. More adherent deposits may require power tool cleaning (St2 or SSPC-SP3) or brush-off blast cleaning (Sa1 or SSPC-SP7/NACE No 4).

The above surface preparation processes are all defined in AS/NZS 2312, and the relevant SSPC/NACE documents.

4.5 Storage, Handling and Erection

Storage of weathering steel sections and plates should ensure that the protective rust patina continues to develop following preparation of the surface, as discussed above. This means that, in ideal conditions, the steel will be stored such that each surface is alternately wetted by rain; or preferably hosed down daily for one week, and dried naturally after every wetting. Particular care must be taken to ensure that plates and sections are not stored so that they become permanently wet, or entrap moisture or dirt. This may easily occur, for example, if a plate is supported so that it deflects upwards and thus provides a water collecting area. Covering with plastic or tarpaulins is not recommended as it promotes condensation and prevents the alternate wetting and drying.

Contamination of the surface should be avoided. This may arise from concrete, mortar, asphalt, coating, oil or grease. In particular, marking the surface for reference during fabrication with wax crayons should be avoided, since this marking can be very difficult to remove. Consider hard stamping for identification of members or joints.

The use of metal slings for handling should be carefully controlled, since they can damage the developing surface protection layer on the steel. While this will eventually redevelop over time, it will give an uneven appearance until removed by weathering.

During erection, continue to protect the sections from contamination and damage. Site welded joints may require special treatment, such as grinding off excess weld on upper surfaces of flanges to avoid potential corrosion traps, and spot abrasive blast cleaning to ensure that all surfaces weather to a uniform colour in a similar period of time.

4.6 Final Site Cleaning

Where care has been taken in handling, storage and erection, it may be possible to avoid any final site cleaning. However, if contaminants have been allowed to accumulate they must be removed, either by washing, by chemical means, or by a site blast clean. Similarly, areas where severe physical damage has occurred may also require blast cleaning after any repair (such as heat straightening).

4.7 Protection of Piers and Abutments

If there is any risk of piers and abutments being stained by rust laden water run-off during erection, consideration should be given to providing temporary protection by wrapping them with polyethylene sheeting or its equivalent. This sheeting should remain in place and be kept free of damage until the final construction inspection is made. See Section 3.8 for detailing for stain prevention.

In the case that the sub-structure develops stains, they may be removed by abrasive blasting, or with a commercial cleaning solution after completion of construction.

4.8 Guardrails and Light Poles

Guardrails and light poles on weathering steel bridges should, where possible, be connected to the concrete deck rather than directly to the supporting steel beams. In most instances these will be galvanized steelwork, with an additional barrier coating or sealant to minimise the risk of crevice corrosion, see Section 3.11.

Image courtesy of www.steelconstruction.info

5. In-service Inspection

5.1 Requirements for Inspection of Weathering Steel Bridges

All bridges, in whatever material, require periodic inspection to confirm that they are performing satisfactorily and to identify and mitigate defects at the first opportunity. A weathering steel bridge, properly designed and detailed, and in the correct environment, should deliver trouble free performance. However, regular inspection of the bridge structure will assist in the early detection of potential issues, and their prompt remediation will assist to minimise the risk of more significant problems in the future.

All parts of the bridge should therefore be designed to be readily accessible for an appropriate level of inspection.

5.2 Level 1 Inspections (Routine)

Level 1 Inspections (Routine) of weathering steel bridges should be carried out by a suitably trained bridge inspector, as described in Table 5 of (Austroads 2004). The surface condition of the protective rust patina is a good indicator of performance. An adherent fine grained rust patina indicates that corrosion is progressing at an acceptable rate, whereas coarse laminated rust layers and flaking suggests unacceptable performance. Other signs to look for and areas to investigate during visual inspection include:

- Leaking expansion joints.
- Accumulation of dirt or debris.
- Moisture retention due to overgrown vegetation.
- Faulty drainage systems.
- Condition of sealants at concrete / steel interfaces.
- Excessive corrosion products at bolted joints ("pack rust").

If any issues are noted during these inspections, the cause should be identified and the problem rectified as soon as possible.

5.3 Level 2 Inspections (Condition Assessment)

This level of inspection should be undertaken every 3 years by an accredited inspector, as described in Table 5 of (Austroads 2004). Provided that provisions have been made for it in the design, the routine inspection described above will pose no particular difficulties. However, the more detailed inspection of weathering steel bridges differs in a number of respects from, and in general is more difficult than, the inspection of coated carbon steel bridges.

One of the advantages of weathering steel is that the surface can be seen directly. However, whilst a heavily corroded surface will be obvious, an inspector must be familiar with the various colours (see following section), textures and general appearance that the rust patina can assume when exposed to different environments in order to judge whether or not the patina is acting in a protective manner. Furthermore, visual appearance on its own may be unreliable and mechanical or other tests may be necessary to determine whether or not the film adheres to the underlying steel base.

One problem which may arise with many such tests (for example wire brushing, or preparation of the surface for ultrasonic investigation) is that the appearance of the protective film may be changed; it will take time for this to return to a uniform appearance.

Whilst design against fatigue should ensure that cracking does not occur during the service life of the bridge, detailed inspection is required to confirm that this is so. As described below, detection of fatigue cracks in weathering steel bridges can be more difficult than detection of cracks in coated steelwork.

5.4 Surface Appearance

An inspector must be able to distinguish between a protective and a non-protective rust coating. Normally this can only be done at close range (within 1 metre distance). The appearance will give the first indication of the quality of the protective film. Whilst only experience can make an inspector expert in such matters, some guidelines are given below.

In colour the protective rust coating should begin as yellow orange after the initial stage of exposure, becoming light brown, and finally chocolate to purple brown (ranging between AS 2700 Colour reference R65 Maroon, and Colour reference X64 Chocolate). See Figure 5.1 for an example of 6 months old patina (left) and a fully formed patina after 8 years (right). Note that in some lighting conditions its appearance can vary from metallic grey to purple.

In texture, the protective rust coating should be tightly adhering, with a relatively smooth surface, and capable of withstanding hammering or vigorous wire brushing (although, as noted earlier, such treatment will affect the appearance, exposing a lighter layer which will take some time to re-darken). A dusty texture, in which loose particles can easily be rubbed off by hand, is common in the early stages of exposure. Granular or flaky appearances are danger signs of a poorly performing surface.

The timing of the colour and texture changes can vary with atmospheric conditions and the degree of direct exposure to rain. A rural, unpolluted atmosphere (typical of most rural areas of Australia, Corrosion Category C2 regions, as discussed in Section 2.3.1) or sheltered interior beams, will result in a lighter colour and dusty texture, taking significantly longer to change, potentially up to 16 years (or longer). The steel composition can also affect this – the greater the extent of alloying elements, the darker the final colour.

Figure 5.1
Example of a 6 month old patina (left) on Papakura Railway Bridge, and a fully formed patina, after 8 years of service, on Mercer to Longswamp Off-Ramp both in New Zealand.

In New Zealand, it has been identified that the protective patina may take up to 8 years to fully form in ideal conditions; this may increase up to 16 years (or more) in areas with higher time of wetness.

If the condition cannot be reliably ascertained, it may be necessary to remove part of the protective layer to determine the extent of pitting and to measure the section loss. However, note the limitations with measuring the steel thickness given below.

It should be noted, that in polluted and/or high salinity environments, the darker colour that implies the patina is formed, may develop within a shorter time frame (from 2 to 8 years). However, evidence has shown (Morcilli et al 2013) that this does not mean that the patina has fully formed. Therefore, monitoring the texture of the surface and measuring the steel thickness will assist in determining when the patina has achieved its protective properties.

5.5 Measuring the Steel Thickness

While the condition of the protective rust patina should be regularly monitored (as discussed above), it is recommended that the measurements of the corrosion rate should be undertaken every 6 years in a C3 environment or every 12 years in C2. This is done by measuring the remaining steel thickness at clearly identified points of the structure. These reference points should be defined on the as-built drawings, or in the bridge maintenance manual, along with the original (reference) thickness measurements taken at the end of the construction period, using callipers and/or the use of an ultrasonic thickness gauge. Measuring internal surfaces is quite difficult using mechanical means.

If over time, it is identified that the corrosion rate is higher than the rate the corrosion allowance was originally based upon, then remedial measures may need to be considered. Note that the corrosion rate is usually higher during the first 10 years of exposure, after which the lower steady state corrosion is reached. Therefore a minimum of 20 years of data is required, unless significant unexpected section loss during the period is identified.

Portable ultrasonic thickness gauges are available to measure the actual steel thickness. However it may be challenging to get an accurate reading, if the patina is still forming and the surface is still rough and easy to remove by hand. Because of this, it is also recommended that removable weathering steel coupons are installed to more accurately monitor the patina formation and measure the corrosion rate.

Allowance should be made for the installation of a minimum of two sets of test coupons on weathering steel bridges, on the primary structural members. The coupons should be cut from the same weathering steel plate used in the bridge, with the same surface preparation (as discussed in Section 4.4)

A total of 30 coupons, cut to 150 x 100 x 5mm (or the thinnest plate available for that bridge), to be installed per bridge, of which 15 are installed on the outer girder, that is exposed to the prevailing weather, and 15 on an inward facing girder surface, that is sheltered from the sun and rain washing. A set of three coupons per side could then be removed and tested on years 6, 12, 18, 24, and 36, to monitor the patina formation and confirm the section loss (and corrosion rate) by testing to ASTM G1-03(2011).

5.6 Detection of Fatigue Cracks

In a coated carbon steel bridge, the first indication of a fatigue crack is often the colour contrast between the coated surface and the rust stain in the vicinity of the crack. Such obvious signs will be absent in weathering steels; indeed, observations of crack growth in fatigue tests of weathered steel beams has shown that fatigue cracks less than 150mm long are very difficult to find by visual inspection. In actual bridges, the shortest crack that can be detected is likely to be even longer, since the crack forms a crevice which completely fills with rust during the service exposure.

The best course of action is to have a Welding Inspector, qualified to Clause 7.2 of AS.NZS 1554.1, conduct a visual inspection for cracks in potential locations, followed by a magnetic particle inspection for confirmation if that location contains a suspected crack. Further detection using ultrasonic testing is recommended on those locations, with the removal of the rust patina for an accurate testing, where the ultrasonic testing will quantify the size and extent of the crack.

After the proper maintenance has been performed, the removed protective rust patina at the location will have to reform to regain its corrosion resistance properties. This is purely an aesthetic problem only, as once the layer has reformed the weathering steel will perform as expected.

6. Maintenance

6.1 General

Routine maintenance of weathering steel bridges consists primarily in ensuring that the bridges are performing satisfactorily, and that they will continue to do so. It may include routine and/or minor remedial works as listed below; major works are described later under rehabilitation.

Such maintenance activities are usually undertaken based on the inspection findings, as discussed in Section 5.

Highway bridges, by their nature and use, accumulate debris; they become wet from condensation, leaky joints and traffic spray, and are exposed to salts and atmospheric pollutants.

Different combinations of these factors may create exposure conditions under which weathering steel may not form a protective rust coating and, for the continued satisfactory performance of the bridge, maintenance must be directed to preventing or rectifying such conditions.

6.2 Maintenance Procedures

The following examples illustrate the maintenance procedures which may be required, depending on the results of inspection:

– Remove loose debris with a jet of compressed air or with vacuum cleaning equipment.

– Remove any poorly adhering layers of rust.

– Remove wet debris and aggressive agents from the steel surfaces by high pressure hosing. This is particularly important where the surfaces are contaminated with salt.

– Trace leaks to their sources (on a rainy day or by hosing the deck near expansion joints and observing the flow of water). Repair all leaky joints.

– Clean drains and down pipes.

– Remove vegetation from the vicinity of the bridge.

– If necessary, install new drainage systems to divert water from superstructure and substructure.

– In the event of "pack-out" of crevices at bolted joints, then the edges of the joint should be sealed with an appropriate sealant.

6.3 Graffiti Removal

As with other forms of uncoated construction, such as reinforced or pre-stressed concrete, the removal of graffiti from weathering steel bridges is difficult, so measures to discourage public access to the girders should be considered. However, this should be balanced with the need to provide access for inspection, monitoring and cleaning.

There are different methods to address the issue related to graffiti, the following options can be considered:

– Apply an anti-graffiti coating at problem areas on the bridge, usually around the abutments. However, this will prevent the patina formation in those areas.

– Apply a citrus based cleaner to the graffiti, with 24 hours of its application, before it is fully cured. Then low pressure water clean at 4000 psi.

– Fully remove the graffiti and underlying protective patina layer, with high pressure water jetting at 10,000 psi. This option will fully remove the patina layer as well, resulting in a patch look until it is reformed again.

– Use dry ice for removing graffiti, see (APT International 2010)

– Leave the graffiti if not objectionable, as it will eventually be absorbed into the patina as it forms.

Lune West Bridge, Lancashire, England. Image courtesy of Jacobs

7. Rehabilitation of Weathering Steel Bridges

7.1 General

When a weathering steel bridge has corroded to an extent that further deterioration cannot be prevented by the simple maintenance procedures described earlier, rehabilitation may be required. Bridges designed, detailed and constructed in accordance with the guidelines given in this publication should not reach this stage unless circumstances beyond the control of the original design arise (for example a new industrial complex causing severe pollution is built close by). However, there are a few existing weathering steel bridges, in the Northern Hemisphere, where performance has been less than ideal, probably because some of the guidelines were not appreciated at the time of design and construction. This section is therefore also intended to assist those responsible for the rehabilitation of such bridges.

Rehabilitation may involve sealing of crevices, removal of poorly formed patina, and possibly coating of the corroded weathering steel. An alternative which has occasionally been used is the enclosure of the whole structure, although this is only likely to be economically viable in very unusual circumstances.

7.2 Sealing of crevices

Since the corrosion in crevices can be one of the major problems related to section loss, rehabilitation of such areas is a necessary preliminary to other work. Crevices can be treated as described below, depending on the type of detail and the degree of corrosion:

- For non-critical connections, such as at bolted restraints or bolted brackets, if practicable disassemble the connection, prepare the surface to a minimum of SSPC-SP10/NACE No 2 (similar to Sa 2 ½), apply a suitable coating, such as a non-conductive barrier coating, and reassemble. Alternatively;
- For critical connections, such as splices at the main girders, or other connections that cannot be disassembled, apply a penetrating sealer (such an low viscosity epoxy, moisture cured urethane, or high ratio calcium sulfonate primer) to displace any water, caulk all edges with a moisture-cured polyurethane sealant, then stripe and coat the connection (lapping 50mm on the surrounding steelwork) with a compatible coating.

7.3 Use of Protective Coatings

The coating of a weathering steel bridge has the same issues and challenges as a carbon steel bridge. In both cases, preparing the surface for coating is essential. The suitability of abrasive blasting, either dry or wet, low pressure water cleaning, or high pressure water jetting is dependent on the environmental restraints, accessibility and logistics for undertaking the work.

As part of preparing the surface, the refurbishment methodology should ensure the removal of salt and other contaminates, especially in deep pits. This includes choosing the appropriate coating system, based on the bridge condition, which should be undertaken in accordance to AS/NZS 2312.1:2014 and (Clifton 2013).

7.4 Inspection and Maintenance of Coated Weathering Steel

Inspection of coated weathering steel is generally similar to that of coated carbon steel bridge, although the exact symptoms of breakdown may differ. It is recommended that a NACE CIP Level 2 (or higher) coatings inspector is employed to undertake the inspection of a coated weathering steel bridge.

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Appendix A:
Determination of Site-Specific Atmospheric Corrosivity Category

The guidance given in Section 3.2 of the *Australian Steelwork Corrosion and Coatings Guide (ASCCG)* (Clifton et al 2013) should be used when determining the atmospheric corrosivity category of the nominated site, by determining the first year corrosion rate of mild steel taking into account both the macro- and microclimate. The main governing factor in this case, is the corrosivity category of unwashed surfaces.

The following examples outline the steps required to determine the atmospheric corrosivity category.

Example A.1: Bridge located at Parramatta, NSW.
A bridge is to be built in Parramatta, within 10km from Sydney Harbour, and the prevailing wind is a North Westerly, i.e. blowing from the site toward sea.

Step 1: Determine the Macroclimate Atmospheric Corrosivity Category:
The site macroclimate atmospheric corrosivity category is taken as 25μm/annum, from Figure A4 of AS 4312.

Step 2: Determine the Microclimate effects:
– For shaded area, + 5μm/annum (Section 3.2.3.1 of ASCCG) = 30 μm/annum.

– For unwashed surfaces, take the unwashed factor as, C_{uw} = x1.2 (Section 3.2.3.2(d) of ASCCG) = 36 μm/annum.

The microclimate atmospheric corrosivity category for this site is taken as 36 μm/annum, which is equivalent to C3 (Medium).

Hence weathering steel can be used in this site, with the corrosion allowance taken as 1.5 mm, as discussed in Section 3.3.

Example A.2: Bridge located at Whyalla, SA.
A bridge is to be built in Whyalla, within 1 km from the Spencer Gulf, and the prevailing wind is a South Easterly, i.e. blowing from the sea toward the site; but the site is sheltered by the surrounding buildings.

Step 1: Determine the Macroclimate Atmospheric Corrosivity Category:
The site macroclimate atmospheric corrosivity category is taken as 15μm/annum (rounded up), as given in Table A1 of AS 4312.

Step 2: Determine the Microclimate effects:
– For shaded area, + 5μm/annum (Section 3.2.3.1 of ASCCG) = 20 μm/annum.

– For unwashed surfaces, take the unwashed factor as, C_{uw} = x2.0 (Section 3.2.3.2(b) of ASCCG) = 40 μm/annum.

The microclimate atmospheric corrosivity category for this site is taken as 40 μm/annum, which is equivalent to C3 (Medium).

Hence weathering steel can be used in this site, with the corrosion allowance taken as 1.5 mm, as discussed in Section 3.3.

Example A.3: Bridge located at Yorke Peninsula South, SA.
A bridge is to be built in Yorke Peninsula South, within 3 km from the Spencer Gulf, and the prevailing wind is a South Westerly, i.e. blowing from the sea toward the site.

Step 1: Determine the Macroclimate Atmospheric Corrosivity Category:
The site macroclimate atmospheric corrosivity category is taken as 35μm/annum (rounded up), as given in Table A1 of AS 4312.

Step 2: Determine the Microclimate effects:
– For shaded area, + 5μm/annum (Section 3.2.3.1 of ASCCG) = 40 μm/annum.

– For unwashed surfaces, take the unwashed factor as, C_{uw} = x2.2 (Section 3.2.3.2(b) of ASCCG) = 88 μm/annum.

The microclimate atmospheric corrosivity category for this site is taken as 88 μm/annum, which is equivalent to C4(High).

Hence weathering steel cannot be used in this site.

Example A.4: Bridge located at Learmonth, WA.
A bridge is to be built in Learmonth, within 3 km from the Exmouth Gulf, and the prevailing wind is a South-south Westerly, i.e. blowing from the site toward the sea.

Step 1: Determine the Macroclimate Atmospheric Corrosivity Category:
The site macroclimate atmospheric corrosivity category is taken as 10 μm/annum (rounded up), as given in Table A1 of AS 4312.

Step 2: Determine the Microclimate effects:
– For shaded area, + 5μm/annum (Section 3.2.3.1 of ASCCG) = 15 μm/annum.

– For unwashed surfaces, take the unwashed factor as, C_{uw} = x1.2 (Section 3.2.3.2(a.ii) of ASCCG) = 18 μm/annum.

The microclimate atmospheric corrosivity category for this site is taken as 18 μm/annum, which is equivalent to C2 (Low).

Hence weathering steel can be used in this site, with the corrosion allowance taken as 1.0 mm, as discussed in Section 3.3.

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