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EUROPEAN DESIGN GUIDE FOR THE USE OF WEATHERING STEEL IN BRIDGE CONSTRUCTION

2ND EDITION

Bridge Committee

Nº 143 | **2021**

ECCS AC3 Bridge Committee

European design guide for the use of weathering steel in bridge construction

2nd Edition, 2021

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PREFACE

Bridges are an important part of Europe's transport infrastructure and are intended to fulfil numerous, but also different tasks. While some bridges are simply about saving time when transporting people and goods from one side of a valley to the other, today's bridges are becoming longer and longer and connect countries, continents and cultures with each other. Whereas in the early days the focus was purely on economic aspects, nowadays bridges also serve as symbols and landmarks.

In many cases of today's award practice, the type of construction and choice of material is determined solely by economic aspects, especially in the case of structures that are intended to provide simple and functional transport from point A to point B. It is precisely in the case of these bridges that we are increasingly finding damages today, sometimes associated with massive long-term effects on traffic. Therefore, the awareness of ensuring the durability of the infrastructure and thus the mobility of people as well as the exchange of goods is coming more to the fore.

Corrosion damage is a frequent cause of limited serviceability of bridges. This can be observed across a large number of bridges, regardless of the construction material. The erroneous belief that this problem could be solved by constructing everything in concrete, while at the same time reducing construction costs, has led to the fact that today many concrete bridges have to be replaced well before they reach their calculated service life – often by steel or steel composite superstructures.

Corrosion damage in steel components can be permanently prevented. The traditional and still most frequently used method is a multi-layer protective paint system. However, this has the disadvantage that it has to be renewed several times during the life cycle of a bridge. On the other hand, there are three almost maintenance-free alternatives that have become increasingly important in recent years: hot-dip galvanised steel with a greater layer thickness, stainless steel and weathering steel. In terms of circular economy, all three variants have the advantage that they can be fully recycled and thus protect the environment and resources.

While hot-dip galvanised steel needs a further additional layer, stainless steel and weathering steel are supplied quasi ex works with integrated corrosion protection without any additional layer. The crucial difference is that weathering steel generates comparable construction costs as a painted steel, while stainless steel is significantly more expensive and its use must be very well justified, e.g. by a very aggressive atmosphere. In most cases, however, weathering steel offers the most economic and environmental advantages. It is almost maintenance-free, if properly designed and constructed, and does not lead to consequential costs or traffic disruption.

At the same time, weathering steel provides similar mechanical properties as usual structural steel. Hence the same codes for design, fabrication and erection apply and no extra effort arises. This document is intended to supplement the well-known standards for design and execution and to serve as a guidance for the use of weathering steel in steel and composite bridge construction. For this purpose, basic background knowledge on weathering steel is given, numerous worked examples are shown, and many recommendations from international experiences have been developed.

This document updates an earlier ECCS document from 2001: The Use of Weathering Steel in Bridges; Publication No. 81 of the European Convention for Constructional Steelwork (ECCS) [5]. Since the publication at that time, the Eurocodes have become established throughout Europe and various other standards and national guidelines on weathering steel construction have been updated, in some cases substantially. In addition, extensive new knowledge about the use of weathering steel has been gained through progressive practical application and various research projects. For these reasons, there are significant differences between the current document and the previous publication.

This document has been prepared by the Chair of Steel Construction at TU Dortmund University in cooperation with the ECCS AC3 Bridge Committee and other European experts. The contribution of all active members and guests of the ECCS AC3 Bridge Committee to the reviewing and commenting of this publication is gratefully acknowledged. The members and guests of the ECCS AC3 Bridge Committee are listed below in alphabetical order:

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Dennis Rademacher
Chairman of ECCS AC3 Bridge Committee

CONTENTS

1 INTRODUCTION

The concept of weathering steel dates back to 1928 with the development of the Union-Baustahl by the Vereinigte Stahlwerke AG in Germany and the commercial brand COR-TEN® developed by US Steel Corporation in the early 1930s [15]. It was originally meant to be used in railway wagons. In the years that followed, this type of steel achieved great success in bridge construction as well and is regularly produced as a standard construction material today.
When designed and detailed correctly and used in the correct environment, weathering steel performs excellently. Properly designed bridges made of weathering steel provide almost maintenance-free structures of attractive appearance without the need for an additional coating or paint system to prevent corrosion. They pose no design, delivery, fabrication, assembly or inspection problems and are highly recommended as an economical and ecological solution in many locations.

The purpose of this publication is to provide the necessary guidance for the durable and reliable use of weathering steel in bridges and other structures. This publication covers all relevant issues from the material, design, construction and fabrication through the inspection and maintenance to the rehabilitation of weathering steel bridges.

1.1 Considered guidelines

To assist users, authorities in a number of European countries have produced codes or specifications and other bodies (researchers, fabricators, steelmakers) have produced guidelines in varying degrees of detail. Without claiming completeness, the following documents are considered in this European design guide:

Europe (ECCS):

The Use of Weathering Steel in Bridges; ECCS Publication No. 81 [5] – previous design document of the ECCS for the use of weathering steel in bridges

Belgium:

Acier auto-patinable [2]

Czech Republic:

TP 197 - Mosty a konstrukce pozemních komunikací z patinujících ocelí [9]

Směrnice pro používání ocelí se zvýšenou odolností proti atmosférické korozi [12]

France:

Aciers autopatinables – Recommendations pour leur utilisation en structure des ponts et passerelles [1] – under revision at the writing of this design guide

Germany:

DASt Richtlinie 007 - Lieferung, Verarbeitung und Anwendung wetterfester Baustähle [3]

Merkblatt 434 – Wetterfester Baustahl [6]

Spain:

EAE – Instrucción de Acero Estructural [4]

Switzerland:

SteelDoc 03/05 – Wetterfester Stahl [11]

United Kingdom:

CD 361 - Weathering steel for highway structures [8]

SCI P185, GN 1.07 – Use of weather resistant steel [10]

In addition, one publication from another continent is considered:

New Zealand:

HERA Report No. R4-97 – New Zealand Weathering Steel Guide for Bridges [7]

2 WEATHERING STEEL

2.1 What is weathering steel

Weathering steel is a structural steel with low content of alloying elements that, in suitable environments, forms an adherent protective oxide layer, also called “patina”, which minimises further corrosion and therefore weathering steel may be used without an additional coating. For this reason, its technical name is “structural steel with improved atmospheric corrosion resistance” [33]. The proportion of all the specific alloying elements such as copper, chromium, silicon, nickel is in total only a few per cent. Despite the low addition of alloying elements, weathering steel has similar material, technological and workmanship properties as the non-alloyed structural steel. The design and use of weathering steel are also comparable, if its specific requirements given in this and the respective national guidelines are considered. Also, some grades of weathering steel with high phosphorus (about 0.1 %) exist but are not recommended by the authors of this European design guide to use for structural, load-bearing members in bridge construction or even forbidden in some European countries due to a limited impact strength and poor weldability.

After its development in the 1920s originally for railway wagons (see Section 1), weathering steel has also been established worldwide for many decades for the use in bridge construction and other steel structures, as well as a facade material and for sculptures. In Europe, weathering grades are present in the harmonised standard product EN 10025-5 [33]. In the meantime, there are many individual licensed brand names for weathering steel from the various steel manufacturers, such as COR-TEN®, SSAB Weathering®, Arcorox®, Indaten® or DIWETEN®. Some of the available steels also differ slightly from the defined grades of EN 10025-5 [33], in terms of chemical composition, mechanical properties or delivery condition. Plates of weathering steel in grade S355 are available from stock in various thicknesses, while the newly introduced weathering steel in grade S460 is currently being produced to order.
For long products, the industrial production of rolled sections in weathering grades began in Luxembourg in the 1970s. Today, also much of the section range according to EN 10365 [35] is available in S355W and S460W.

All structural steels corrode, at a rate which is governed by the access of moisture, oxygen and other compounds in the atmosphere to the metallic iron and its alloys. As this process continues, the oxide (rust) layer becomes a barrier restricting further ingress of moisture and oxygen to the metal and slowing down the rate of corrosion.

The big difference between the oxide layers formed on the uncoated surface of weathering steel and non-alloyed structural steel is the significant higher adherence to the base material and much more compact structure. The crystalline rust layers of the uncoated non-alloyed structural steel are very porous and may detach from the metal surface after a period of time. In contrast, the alloying elements of the weathering steel and components in the atmosphere form an amorphous and protective oxide layer on the surface of the weathering steel in a few years, as shown in Fig. 2.1. The main influences on the formation of the protective oxide layer, are the local environment and the structural detailing of the construction to ensure the required alternate wetting and drying. Assuming that there is no significant negative change in the environmental conditions, and with regular inspection, the lifetime of a weathering steel bridge is more than the calculated lifetime of 100-120 years.
Fig. 2.2 shows the comparison of the corrosion losses of unprotected non-alloyed steel and weathering steel according to the calculation values of ISO 9224 [45] for a "medium corrosive" environment of class C3.

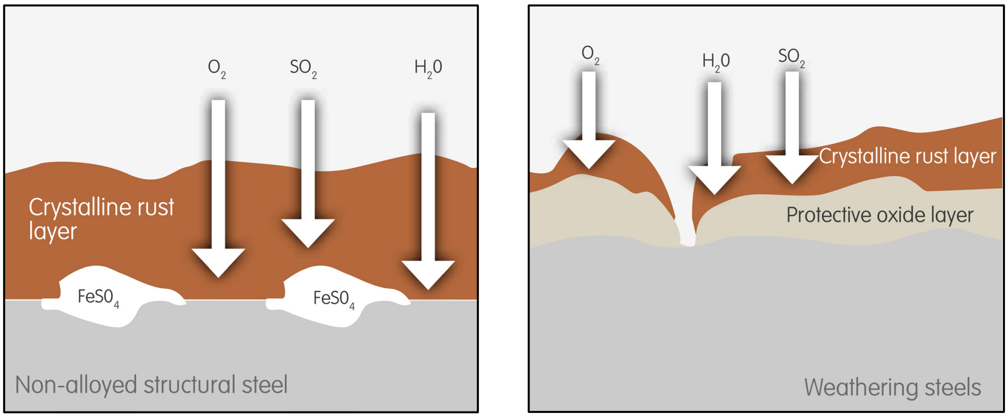


Fig. 2.1: Oxide layers on the surface of non-alloyed structural steel and weathering steels [26]

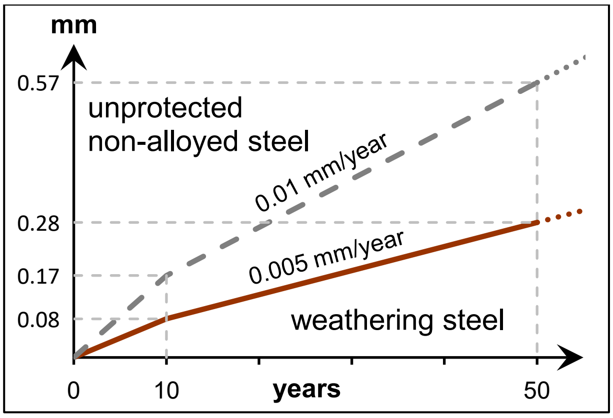


Fig. 2.2: Annual corrosion loss of unprotected non-alloyed steel and weathering steel (in mm) according to ISO 9224 [45] for a "medium corrosive" C3 environment (values for weathering steel from the previous ISO 9224:1992)

The appearance, texture and maturity of the oxide layer depends on the duration and degree of exposure, as well as the surrounding atmosphere. With time, the oxide layer turns from a red-orange colour to a dark brown colour (sometimes even with slight shades of purple). Once the oxidisation phenomenon is stabilised, the oxide layer is a rust-brown colour with a fine-grained appearance. Fig. 2.3 shows examples of possible appearances of the oxide layer developed in different conditions with different times of exposure and lighting conditions.

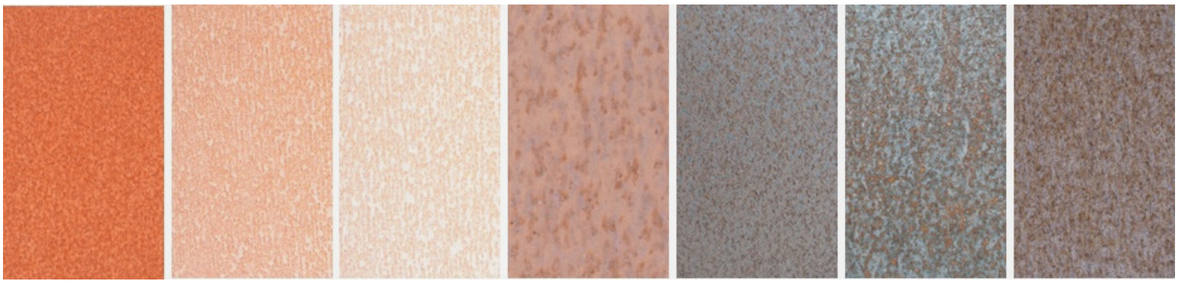
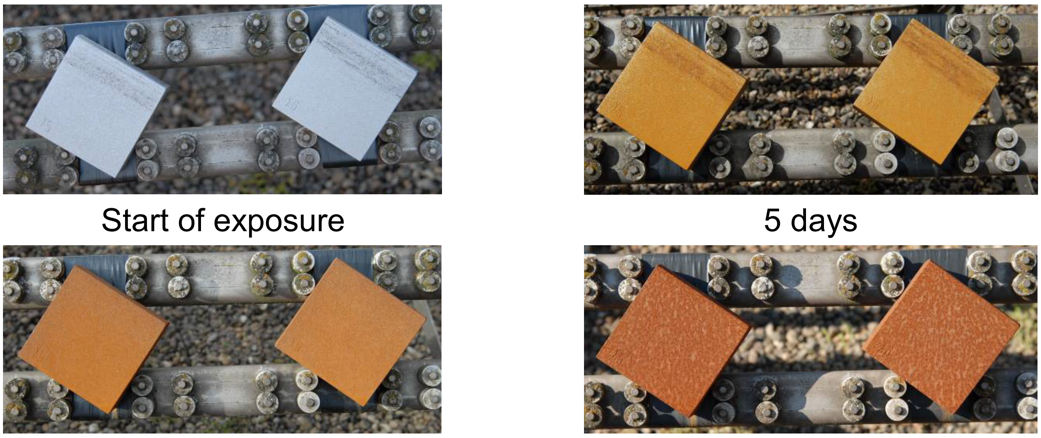


Fig. 2.3: Example of possible oxide layer appearances developed under different exposure conditions

The darker shades are generally produced in industrial environments. In rural environments, the oxide layer forms more slowly, and the shades produced are generally lighter. Surface blasting enables the formation of a regular oxide layer with a uniform appearance and is generally recommended, especially when a uniform appearance is required in a short time. An example for the development of the surface appearance within about the first year of exposure is given in Fig. 2.4. Fig. 2.5 shows the steel structure of a composite bridge during assembly without an oxide layer and Fig. 2.6 shows the completed bridge after opening and some weeks of outdoor exposure.



Start of exposure

5 days

1 month

13 months

Fig. 2.4: Development of test cuttings at CRP H. Tudor, Esch-sur-Alzette

Fig. 2.5: Composite bridge during assembly of steel structure without oxide layer, San Martin à Fontes, France

Fig. 2.6: Composite bridge after opening and some weeks of outdoor exposure, San Martin à Fontes, France

2.2 Benefits of weathering steel

Initial cost benefits

The use of weathering steel can often reduce the construction costs of a bridge by saving the painting costs (of a comprehensive protective high-quality paint system used for bridges with e.g. four layers each of 80 µm) and construction time. The savings offset a slight increase in material costs due to

- slightly higher purchasing costs for the raw material and the consumables
- allowance for corrosion loss of structural steel
- additional care and effort in detailing, such as precautions to avoid rust staining

Reduced construction time

The omission of an organic coating system (paint system) will result in reduced construction time, an advantage to the contractor and ultimately the client. In addition to the elimination of the preparation, application and drying time of the paint layers, less protection is required during transport and no repair of any defects in the sensitive corrosion protection system is necessary.

Reduced life cycle cost and duration of maintenance works

The major advantage of using weathering steel in bridges is the significant reduction of maintenance costs over the life cycle of the construction. If detailed correctly, the maintenance costs of weathering steel bridges are negligible compared to the costs of regular repainting a steel structure. This also greatly reduces external costs, such as those resulting from traffic management and traffic delay whilst maintenance operations are carried out, especially in places that are difficult to maintain like bridges over busy railway lines or highways. To ensure that the bridge continues to perform satisfactorily, only some inspection and perhaps cleaning or occasional re-treatment of limited areas is required, as is usually the practice for painted bridges.
A well-functioning bridge made of weathering steel is therefore almost maintenance-free and so has advantages in terms of operation compared to painted structural steel and reinforced concrete bridges.

Environmental and safety benefits

The appliance and maintenance of paint systems can be harmful to the health of the operatives, for example by the release of hazardous VOCs (volatile organic compounds) and can also cause environmental damage. Moreover, degradation of paints release microplastic into the environment. Therefore, health and safety protection for the applicators and extensive environmental measures are required, such as containment and disposal of abrasive blast cleaning residue.
Thus, the omission of an additional paint system by using weathering steel brings significant health and environmental advantages, underlining the sustainability of weathering steel.

Attractive appearance

The protective mechanism of weathering steel in bridges is the formation of a stable oxide layer. Once fully formed and weathered, the appearance of this layer is uniform, usually of a dark brown colour. This colour can blend nicely into the environment, as shown in Fig. 2.7 and the various examples in Section 2.4. In building construction, architects often select weathering steel as an architectural design element to underline the natural and sustainable appearance.

Fig. 2.7: Viaduc de la Scyotte in Grattery, France, completed in 2018

Comparison of weathering steel and painted non-alloyed structural steel

Table 2.1 summarizes different economic and ecological aspects of medium span bridges made of weathering steel, painted non-alloyed structural steel as well as reinforced or prestressed concrete bridges. Especially in terms of life cycle costs and sustainability, weathering steel bridges have clear advantages over the other construction materials.

Table 2.1: **Comparison of different construction materials for medium span bridges**

Aspect	Weathering steel	Painted non-alloyed steel	Reinforced/ prestressed concrete
Initial construction costs (incl. material, fabrication and corrosion protection)	**o**	**o**	**o / +**
Construction time	**++**	**+**	**-**
Life cycle costs	**+**	**-**	**-**
Constraints due to maintenance works	**+**	**-**	**-**
Sustainability	**++**	**+**	**-**
Appearance	natural (uniform rust)	at choice (top paint)	grey (concrete)
o comparable (project-specific), **-** worse, **+** better, **++** much better			

The direct cost comparison depends on many factors and cannot be quantified across the board. In the course of current research projects [18] [19], holistic comparisons were carried out for various bridge types in terms of sustainability.

For the representative example of a rural highway viaduct, the manufacturing costs for the weathering steel variant were comparable to those of the painted non-alloyed steel, whereas the life cycle costs of the weathering steel bridge were more than 6 % lower after 100 years as shown in Fig. 2.8 (left). In terms of the steel superstructure only, the relative savings due to the weathering steel are much higher. But the cost comparison shown here also includes the entire substructure made of concrete, the roadway surfacing, as well as the planning and site equipment. The two steps after 33 and 66 years also consider the replacement of bearings, the complete renewal of the road surfacing, bridge caps and safety devices. The obligatory discount rate for the calculation has been adjusted from 2 % (original calculations in 2012 [19]) to 1 % (calculation in 2021). [19]

The major advantage of weathering steel and the omission of a paint system is primarily reflected in the significantly lower external user costs due to the elimination of road closures for inspection, maintenance and renewals of the paint system. As can be seen in Fig. 2.8 (right), the saving in this example of a viaduct with an average daily traffic of 40,000 vehicles per day is around 10 % and can be even higher for crossing overbridges or higher traffic densities [19]. Considerable savings are also achievable for railway bridges, especially with high traffic densities.

Considering these aspects, the use of weathering steel is even more advantageous over alternative options.

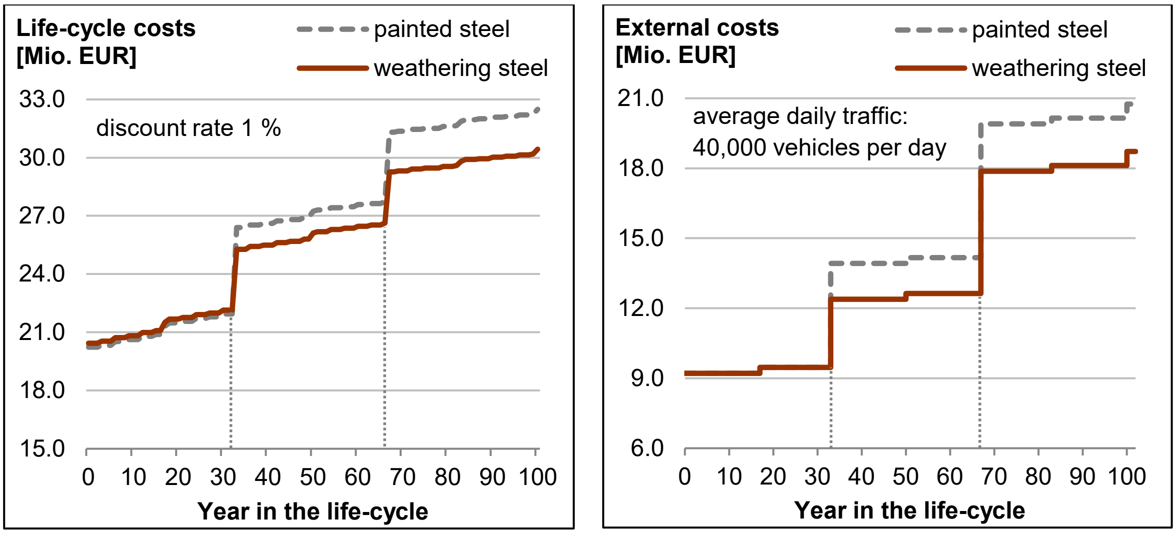


Fig. 2.8: (left) Comparison of the life-cycle costs (LCC) with a discount rate of 1 % and (right) comparison of external costs for the condition-based maintenance strategy and an average daily traffic of 40,000 vehicles per day for a reference rural highway viaduct (total bridge construction incl. steel superstructure, substructure, roadway, planning and site equipment) in absolute values [19]

2.3 Where and how to use weathering steel

2.3.1 The admissible environment

Most rural and urban locations will be very close to the ideal environment, and are well suited for the use of weathering steel.

It is very important that a weathering steel bridge should only be designed for use in a suitable environment. Ideally this should be a largely unpolluted atmosphere where the weathering steel is exposed to alternate cycles of wetting and drying by clean rain. This supports the formation of a very dense, tightly adhering and stable oxide layer. It is generally accepted that a low concentration of sulphur dioxide in the atmosphere can actually assist the formation of the protective layer on weathering steel.

Conversely, the best way to identify whether an environment is satisfactory is by reference to the limited circumstances which are generally not suitable for the use of weathering steel. Those are environments where high concentrations of strong chemical or industrial pollutants are present, where the steel would be exposed to deposition of salt (particularly marine environments) or where members in weathering steel would be continuously wet or damp. Section 2.3.3 contains detailed information on these restrictive circumstances in which weathering steel is not a suitable material.

2.3.2 Corrosivity categories

To estimate the corrosion behaviour of metals and alloys in different corrosive atmospheres, EN ISO 9223 [44] provides a classification, determination and estimation of atmospheric corrosivity. The corrosivity categories defined therein are a technical characteristic of atmospheric environments and form the basis for the selection of materials and corrosion protection measures. In principle, the corrosivity is determined from corrosion losses, which are measured on standard metal samples after one year in the corresponding environment. In addition, an estimation based on information about the respective local environment is possible. Depending on the corrosivity categories of EN ISO 9223 [44], reference values for the corrosion loss of certain metals and alloys can be determined and predicted with EN ISO 9224 [45].

The corrosivity is classified into the six categories from C1 "very low" up to C5 "very high" and CX "extreme”, as shown in Table 2.2. [44] To estimate the corrosivity category, examples of typical environments in the temperate zone (Europe) are also given, although they do not characterise specific local atmospheres such as those in industrial plants.

Recent studies [22] [25] have shown that inland corrosion in Europe can be typically categorized into C2 or, in cases of exceptional pollution, C3. The current atmosphere is getting cleaner and cleaner and highly polluted environments (corrosivity category C4) only occur very rarely in Europe. The increasingly strict environmental protection requirements can lead to, and have already led to, an improvement in the corrosivity categories, for example in industrial areas. The still significant but ever decreasing difference between industrial, urban and rural areas will continue to decrease in the future. The main difference today is between inland and coastal areas. The corrosivity categories in coastal areas of Europe range between C3 and C5, depending on the material, location, topography, weather conditions and other local conditions. In addition, de-icing salt water and spray can lead to increased chloride pollution and higher corrosivity categories (up to C5) in inland microclimatic areas adjacent to or running closely over salted roads (“tunnel-like” conditions).

Table 2.2: **corrosivity categories and typical environments for their estimation according to EN ISO 9223 [44]**

Corrosivity category	**Corrosivity**	**Examples of typical outdoor environment in the temperate zone – only for estimation**
C1	*very low*	*Not relevant in Europe (extremely dry or cold climate)*
C2	low	Low air pollution, e.g. rural areas or small cities
C3	medium	Moderate air pollution or low influence by chlorides, e.g. urban areas or coastal areas with low chloride pollution
C4	high	High air pollution or with significant influence by chlorides, e.g. urban areas with air pollution, industrial areas, coastal areas, not in the area of salt water spray, strong pollution by de-icing salts
C5	very high	Very high air pollution and/or with significant influence by chlorides, e.g. urban areas with air pollution, industrial areas, coastal areas
CX	*extreme*	*Not relevant in Europe ((sub)tropical climate zone)*

For further information on the air pollution mainly by sulphur dioxide and chlorides and the respective concentrations, see EN ISO 9223 [44].

As described in more detail in Section 3.3, the use of weathering steel without additional corrosion protection is not suitable in corrosivity categories C5 and CX. Nowadays, however, this practically only occurs in the case of very high concentrations of chlorides in marine environments directly at the coast or through very significant exposure to de-icing salt, see Section 2.3.3.

For the corrosion behaviour of weathering steel, the temperature, the humidity durations or wet-dry cycles, as well as the content of corrosive substances in the atmosphere (e.g. chlorides or sulphates), are of decisive importance. Since the local microclimate is rarely known and other important influences are not sufficiently reflected in the corrosivity categories, the following Table 2.3 provides reference values for possible, locally applicable corrosivity categories.

Various current studies [12] [14] from different countries provide more detailed information on the currently existing corrosivity categories in relation to the corrosion behaviour of the weathering steel.
In addition, the sulphur content is determined by many local pollution measuring points. If desired or required, the local chloride content can be determined using the wet candle method according to EN ISO 9225 [46].

Table 2.3: **Reference values for possible, locally applicable corrosivity categories based on [6] [25] [44]**

Environmental conditions (weathering, environment, pollution, etc.)	**Possible corrosivity category**
indirect weathering (no direct rain) and good ventilation rural or urban atmosphere with less industry low air pollution ($SO_2 \leq 5$ µg/m³) **and** no significant chlorides ($Cl \leq 3$ mg/(m²·d))	C2
direct weathering (direct rain) and good ventilation rural or urban atmosphere with less industry low air pollution ($SO_2 \leq 5$ µg/m³) **and** no significant chlorides ($Cl \leq 3$ mg/(m²·d))	C2 – C3 strongly dependent on temperature and humidity
direct or indirect weathering and good ventilation urban atmosphere with industry moderate air pollution (5 µg/m³ < $SO_2 \leq 30$ µg/m³) **or** low chlorides (3 mg/(m²·d) < $Cl \leq 60$ mg/(m²·d))	C3
direct or indirect weathering and bad ventilation or moisture trapping (e.g. by dirt nests) rural or urban atmosphere with industry up to moderate air pollution (5 µg/m³ < $SO_2 \leq 30$ µg/m³) **or** low chlorides (3 mg/(m²·d) < $Cl \leq 60$ mg/(m²·d))	C4
direct weathering and good ventilation urban / industrial atmosphere with heavy industry high air pollution (30 µg/m³ < $SO_2 \leq 90$ µg/m³)	C3 – C4 strongly dependent on temperature and humidity
direct or indirect weathering and good ventilation coastal areas (outside saltwater spray) or possible influence by de-icing salt spray → see Section 2.3.3 significant chlorides (60 mg/(m²·d) < $Cl \leq 300$ mg/(m²·d))	C4 strongly dependent on temperature and humidity

2.3.3 Application limits

As for any other construction material, some severe environmental conditions can occur, in which weathering steel can cause durability problems. The performance of weathering steel may not be satisfactory in such environments or local microclimatic conditions and then its use should be avoided. The most common critical environments are presented below.

Highly polluted chemical and industrial environments

Weathering steel should not be used in atmospheres containing high concentrations of corrosive chemical or industrial fumes, especially SO_2. Nowadays, these highly polluted industrial atmospheres are, however, practically excluded by compliance with environmental protection requirements in the common market. Only when the average sulphur content in the atmosphere exceeds a deposition rate of 80 mg of SO_2 per m^2 per day or a concentration of 90 µg per m^3, is a level P3 [44] highly polluted industrial atmospheres considered. According to the British guideline [8], weathering steel may not be used in these atmospheres or where another source of atmospheric pollution makes the use of weathering steel unviable due to the extent of corrosion that is likely to occur.

In recent research [25], even in a highly polluted atmosphere at a heavy industrial production site, an annual average concentration less than 45 µg/m^3 and corrosivity category C3 was measured between 2017 and 2018. Thus, the application limit due to a highly loaded chemical and industrial atmosphere occurs almost nowhere these days.

In case of doubts, the sulphur content can be obtained from the readings of many local pollution measuring points or measured using appropriate methods.

Marine environments

Weathering steel should not be exposed to high concentrations of chloride ions, because they will greatly affect the formation of the protective oxide layer. The hygroscopic nature of salt can lead to permanent moisture even on sheltered surfaces at high humidity levels and thus prevent the formation of a firmly adhering oxide layer. As a result, the weathering steel would continue to corrode at a similar rate as unprotected non-alloyed steel. [7]

This can occur near the coast, or above tidal rivers, where salt spray or salt fogs may be blown by the wind and salt deposited on the steelwork. The salinity in coastal atmospheres depends on many factors like the salinity of the sea, the wind conditions or the local topography and can therefore differ greatly from site to site.

There are various national and international studies [21] as well as measuring stations that can provide an indication of the salinity in the local atmosphere.

The minimum allowable distance of weathering steel structures from the open seacoast to the location varies in the national guidelines. In Germany [3] a minimum distance of 500 m and outside of permanent fog is given. France [1] demands 2 km from the North Sea, English Channel and Atlantic Ocean and 1 km from the Mediterranean Sea. However, it is possible to reduce this distance if the monitoring of the condition of the steel structures near the area under consideration shows that the corrosivity of the site is not influenced by the presence of the watercourse. In the United Kingdom [8] all structures that should be located up to 15 km inland from a coast require a determination of the local airborne salinity level based on a measuring period of one year. This large distance compared to the other countries appears very conservative.

The authors of this European design guide recommend a distance of 1 to 2 km from the coast, depending on the salinity and local conditions like the topography. Deviations should be justified by appropriate local measurements, for example the wet candle method according to EN ISO 9225 [46].

De-icing salt spray or run-off

Critically high concentrations of chloride ions can also occur where parts of structures are subjected to de-icing salt spray from vehicles using the road below, or run-off from surfaces where salt is applied. The exposure of the underside (superstructure) of the overpassing bridge to de-icing salt spray from the road below is largely dependent on the microclimate underneath as a result of its design (especially the abutments and retaining walls) and dimensions.

For the most conventional intersection structures without retaining walls next to the road underneath, the chloride concentrations occurring at the overpassing structure are within acceptable limits. De-icing salt spray and other pollutants disturbed by traffic can spread laterally across the road axis, as overpasses are nowadays usually designed with embankments and set-back abutments. [17]

Critical chloride loads at the overpassing structure would only be reached in "tunnel-like" conditions such as when a road or highway runs between high retaining walls below a wide overpass. This usually only occurs in restricted spaces, such as in urban areas. Salt will then collect, for example, on the bottom flanges of beams (particularly on internal flanges) and bracings or on plate girder bridges whose surfaces are not exposed to rain and the salt is therefore not regularly washed off.

The French guideline [1] includes a calculation method (Eq. 2.1) for the minimum headroom to prevent the “tunnel-like” conditions between a salted road and the overpassing bridge. The minimum headroom *H* is depending on the length *L* of the retaining wall or noise barrier higher than 2 m and less than 6 m from the roadside, see Fig. 2.9, and also including the maximum of 7.5 m. The Equation (Eq. 2.1) considers the ventilation and the configuration around the structure and is based on practical experiences and many examples of execution.

$$H > \text{min. } (4.3\ m + L/25\ ;\ 7.50\ m) \qquad \text{Eq. 2.1} \quad [1]$$

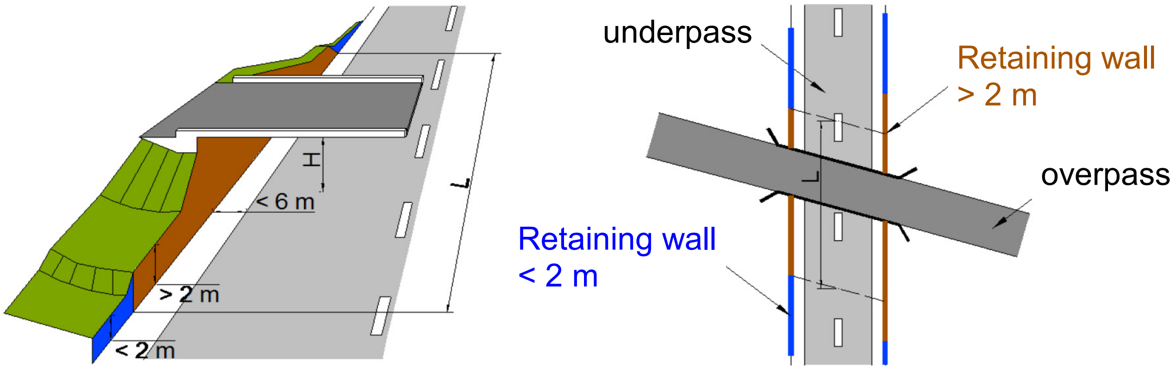


Fig. 2.9: Length of retaining walls to be considered in the calculation of Eq. 2.1 [1]

In the United Kingdom, bridges over roads subjected to de-icing salt spray only have to meet the minimum standard headroom of 5.3 m. In addition, weathering steel should not be used for wide structures over salted roads without any dimensions given. Furthermore, its use is not allowed for structures located within 10 m horizontally of a salted road or where salt-laden water could flow directly over it. The German guideline [3] prohibits the uncoated use of weathering steel in case of unspecified de-icing salt load, and the New Zealand guideline [7] specifies a clear headroom greater than 5.3 m like the British guideline.

Because of its hygroscopic nature, salt maintains a continuously damp environment on the steel surface and is thus doubly detrimental to the formation of a protective oxide layer.

Leaking expansion joints where salt water run-off can result in a higher time of wetness and increased corrosion of the weathering steel structure have to be prevented by appropriate structural detailing, regular inspection and, if necessary, fast repair measures or replacement.

Continuously wet or damp conditions

Weathering steel is not suitable for structures either submerged in water, buried in the ground, or covered by vegetation. In such circumstances the corrosion performance of the continuously damp steel will be the same as that of ordinary structural grades of steel, as the stable protective oxide layer does not form. To prevent this, the minimum headroom for crossings over water without significant wave action has to be 2.5 m and the weathering steel should be no closer than 1 m from the ground [3]. Adjacent trees, bushes or other vegetation, which can prevent the natural drying process, have to be removed.

2.4 Examples and experiences for good practice

The following subsections show various examples of bridges built from weathering steel in different steel grades, sizes, types of construction and environments.

2.4.1 Road viaducts in rural environments

For short and medium span bridges, weathering steel can be much more advantageous than painted non-alloyed steel, whose maintenance operations and costs can become significant in relation to the quantity of steel. Moreover, a modestly sized steel frame placed under the roadway is less aesthetically effective than major bridges with good visibility of the main beams in an open valley.

The use of weathering steel for this type of bridge began relatively early in Luxembourg, as the commercial availability of sections made this a particularly attractive solution from an economic perspective. The first generation of bridges made of weathering steel in Luxembourg was designed at the end of the 1970s, such as the Ditgesbaach viaduct shown in Fig. 2.10, which was completed in 1981.

Fig. 2.10: Ditgesbaach viaduct, access to A7 motorway in Luxembourg

Another representative example of this generation of works is the Mamer Viaduct OA 1001, which was designed very similarly shortly before. The viaduct of 252 m in length transfers the A6 motorway between Luxembourg and Belgium over the Mamer valley, as shown in Fig. 2.11 and Fig. 2.12. It was built between 1977 and 1981 and is constructed as a single span girder chain of eight spans of 31.2 m. The viaduct has separate decks for each traffic direction and a total width of 29.6 m.
Each deck is constructed with six HX1000A x 363 kg/m main beams (comparable to today's HL1000B) with a spacing of 2.6 m. The reinforced concrete slab is 28 cm thick, with a total construction height of around 1.26 m (slenderness ratio h:L = 1:25).

Fig. 2.11: Mamer viaduct, A6 motorway in Luxembourg

Fig. 2.12: Mamer viaduct, A6 motorway in Luxembourg

The Mamer viaduct OA1001 was refurbished in 2008, when the bearings and expansion joints were replaced.
The result of these initial uses of weathering steel in Luxembourg has been positive. The bridges are still in a very good condition, although they have been subjected to very heavy and significantly increased traffic loads in recent years.

Designed subsequently, the Syre viaduct on the A1 motorway between Luxembourg and Trier (Germany) is another successful example of the use of weathering steel in rural settings, as shown in Fig. 2.13. The bridge, with a total length of 372.5 m between the abutments, spans the Syre valley and crosses a two-track railway line as well as a local road and was put into service in 1992. The six main beams of each deck are produced from commercial sections of type HX1000B x 399kg/m and HX1000R x 488 kg/m (comparable to the current HL1000 series).
The main beams were delivered on site with the rolling length between 34 m and 40 m and lifted by crane, see Fig. 2.14 and Fig. 2.15. All the on-site assembly was conducted using high-strength friction grip bolts made of weathering steel. A zinc powder silicate paint to achieve a slip factor of μ = 0.40 was applied to the contact surfaces.
The choice of suitable construction details (beam distance from edge of the deck, abutment conformation) ensured that the load-bearing weathering steel structure is in perfect condition today.

Fig. 2.13: Syre viaduct, A1 motorway in Luxembourg


Fig. 2.14: Syre viaduct erection phase, A1 motorway in Luxembourg

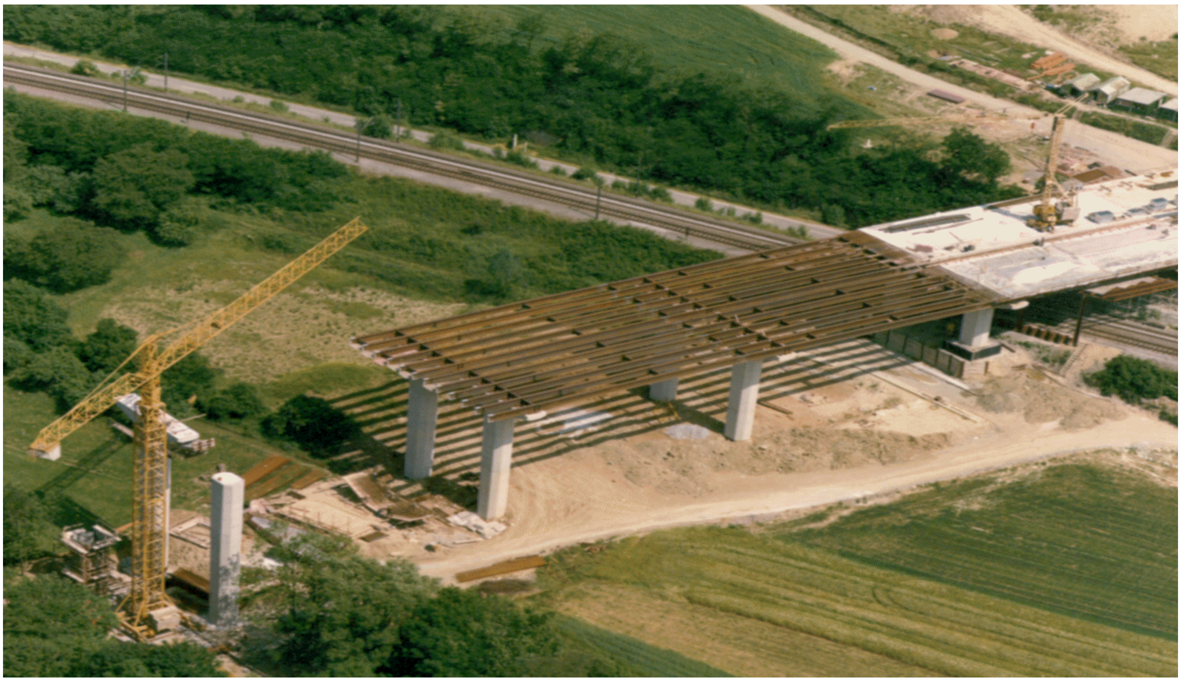


Fig. 2.15: Syre viaduct erection phase, A1 motorway in Luxembourg

Fig. 2.16 shows a typical single-span composite bridge made of weathering steel with a length of 55 m over a canal in Herne, Germany, build in 1975. During this decade, several bridges made of weathering steel were built in Germany, mainly over canals and rivers.

Fig. 2.16: Composite Bridge over a canal in Herne, Germany (construction year: 1975, photo: 2019)

The Viaduc de Sémanet in Dardilly (France), shown in Fig. 2.17 and Fig. 2.18, is an example of a modern composite bridge built until 2018 with a total length of 210 m. The two separate superstructures share a total of 5 common support frames.

Fig. 2.17: Viaduc de Sémanet in Dardilly (Auvergne-Rhône-Alpes, France) built until 2018

Fig. 2.18: Viaduc de Sémanet in Dardilly (Auvergne-Rhône-Alpes, France) built until 2018

Fig. 2.19 and Fig. 2.20 below show an example of a road viaduct in rural environment with decks completely made of weathering steel in Sicily (Italy).

Fig. 2.19: Road viaduct in Sicily (Italy) with decks completely made of weathering steel

Fig. 2.20: Road viaduct in Sicily (Italy) with decks completely made of weathering steel

An example of a composite bridge with a box girder is the bridge over the Cesano River in the Marche Region of Italy, shown in Fig. 2.21 and Fig. 2.22. The three-span continuous box girder is completely welded and was built in 2017.

Fig. 2.21: Composite bridge with box girder over the Cesano River in Marche Region, Italy

Fig. 2.22: Composite bridge with box girder over the Cesano River in Marche Region, Italy

2.4.2 *Bridges over roads*

In Luxembourg, several new road overbridges spanning the existing railway tracks have been built in weathering steel. Designed as continuous beams using hot rolled section with bolted connections, the individual spans range from 15 m to 40 m.

Fig. 2.23: OAT5 Howald bridge over railway line and roadways in Luxembourg

The OAT5 Howald bridge in Luxembourg, shown in Fig. 2.23, is an example of this type of bridge. The bridge had to cross a railway line with 6 tracks without piers, setting the length of the central span to 32.90 m. The width of the bridge is 19.95 m, allowing for the passage of two road lanes.

The vertical railway clearance and the design of the road, determined according to bridges and nearby accesses, severely limited the available height for the deck: about 1.25 m, with a slenderness ratio of h:L = 1:26. The constraints for the installation of the deck were particularly demanding. No disruption to the rail traffic was allowed and complete safety had to be guaranteed for all operations carried out above the electrified tracks.

The deck is made up of a continuous composite structure with 11 main steel beams, spacing 1.75 m, supporting a reinforced concrete slab. The steel frame was assembled without interrupting the rail traffic. To reduce the number of operations required above the tracks, the main beams were pre-assembled in pairs or three braced beams on the worksite area before being lifted onto the piers using a mobile crane, as shown in Fig. 2.24.

All the on-site assembly was conducted using high-strength friction grip bolts made of weathering steel. A zinc powder silicate paint to achieve a slip factor of $\mu = 0.40$ was applied to the contact surfaces, as shown in Fig. 2.25.

Weathering steel has therefore proved to be of great interest in bridges over railway lines, avoiding repainting operations and using rapid assembly to best advantage. Apart from the example mentioned, implementation becomes even more simple for crossing a standard rail section with two or three tracks, thus comprising a span between 20 and 35 m (according to the type of abutment and embankment length). This length can be produced without the need for splicing the main beams.

Fig. 2.24: Erection of the OAT5 Howald bridge in Luxembourg

Fig. 2.25: Erection and bolted connections of the OAT5 Howald bridge in Luxembourg

Fig. 2.26: Composite bridge with weathering steel box girder over a highway in Evry-Courcouronnes, France

As part of the new tram line No. 12 linking Massy to Evry-Courcouronnes in France, two new composite bridges with mixed girders of weathering steel for the outer parts and (unpainted) non-alloyed structural steel for the internal stiffeners and upper plate were built. Fig. 2.26 shows one of these tram and train bridges over a highway with a maximum span of 49 m. The erection of the 6,500 mm wide mixed box girder took place in 2019 and is shown in Fig. 2.27.

Fig. 2.27: Erection of the box girder for the composite bridge in Evry-Courcouronnes, France, in 2019

Fig. 2.28 shows three adjoining composite bridges over railway lines and roadways in Saumur, France. The two bridges on the right side (a road bridge and a pedestrian bridge) date back to 1982 and were supplemented by another road bridge of comparable construction in 2015. All three bridges together create a harmonious overall appearance. After a few years, the different ages of the weathering steel construction can still be seen in the surface appearances, while these become more and more similar with increasing service life. These bridges are a good example of the proven and still absolutely advantageous use of weathering steel in steel and composite bridge construction.

Fig. 2.28: Saumur bridges in Saumur, France, build in 2015 (new bridge on the left) and 1982 (two bridges on the right)

2.4.3 Europe's first road bridges with high strength weathering steel grade S460W

Fig. 2.29: Weathering steel girders at the erection of the composite bridge in Wirkowice (Poland) with a light orange-brown oxide layer after short exposure for several weeks

The composite bridge in Wirkowice in the Lubelskie (Lublin) province of Poland on the Wieprz River, shown in Fig. 2.29 and Fig. 2.30, is the first road bridge in Europe constructed with weathering steel rolled sections of the high strength grade S460J2W and was completed in early October 2020. The HEA 900 rolled sections used in the new steel grade S460J2W+M according to EN 10025-5:2019 [33] allowed a reduction in weight and an increase in bridge clearance compared to bigger sections in S355J2W+M.

Fig. 2.30: Completed composite bridge over the Wieprz River in Wirkowice (Poland) with an orange-brown oxide layer after exposure for six months

For the new Carrington Bridge in Worcester, England, high strength heavy plates of weathering steel grade S460K2W+M according to EN 10025-5 [33] were used for the welded main girders for the first time. The 205-metre-long steel composite bridge is a three-span structure with spans between 64 and 72 metres and crosses the River Severn. After the welded main girders were prefabricated in the fabrication shop in individual girder sections made of the higher-strength weathering steel, the assembly on the construction site was done with bolted connections at the end of 2020, as shown in Fig. 2.31 and Fig. 2.32.
Due to its higher strength compared to the originally planned weathering steel grade S355W, significant material, time and cost savings were possible.

Fig. 2.31: Erection of the Carrington Bridge in Worcester, England

Fig. 2.32: Erection of the Carrington Bridge in Worcester, England

2.4.4 Pedestrian bridges

Weathering steel is also very well suited for pedestrian and cycling bridges that are aesthetically integrated into the environment.

Fig. 2.33 shows a pedestrian and cycling bridge with a 37-metre span build in 2019 in Banleve, Toulouse, France. The welded box-girders made of weathering steel are slightly curved and act as the outer boundary of the deck as well.

Fig. 2.33: Pedestrian and cycling bridge in Banleve, Toulouse, France

The pedestrian and cycling bridge shown in Fig. 2.34 is located in Ernée (Département Mayenne) in the north of France. It was built in 2018 and spans 33 metres over a road. Curved supports and perforated sheets are attached to the load-bearing structure of a box girder, with all components made of weathering steel.

Fig. 2.34: Pedestrian and cycling bridge in Ernée, Mayenne, France

The pedestrian bridge in Kuusijärvi, Vantaa, Finland is completely made of weathering steel, as shown in Fig. 2.35 and Fig. 2.36. It is a medium span bridge with a total span of 126 m supported by a group of four weathering steel columns at the centre and was built in 2019.

Fig. 2.35: Pedestrian bridge in Kuusijärvi, Vantaa, Finland

Fig. 2.36: Pedestrian bridge in Kuusijärvi, Vantaa, Finland

3 DESIGN, DETAILING AND CONSTRUCTION

3.1 Introduction

The various European design codes for steel bridges, which are written mainly for ordinary structural steel, are equally applicable to weathering steel bridges in respect of requirements for strength and stiffness. Like non-alloyed structural steel, the strength is based on nominal tensile yield, which depends on the grade of material (see Section 3.2). Only the fatigue strength of plain members free from welding is slightly restricted due to the roughness of the corroded surface (see Section 3.8). Furthermore, there are a number of requirements to ensure that the weathering steel performs as intended and long-term durability is achieved. In addition to the suitable environment (given in Section 2.3), these mainly concern the general structural detailing of weathering steel construction and its connections (described in Sections 3.5 to 3.7).

To assist users, authorities in a number of European countries have produced codes or specifications and other bodies (researchers, fabricators, steelmakers) have produced guidelines in varying degrees of detail. Without claiming completeness, this design guide considers mainly the (national) documents listed in Section 1.1.

In the following Sections, important design requirements, drawn from several sources, are described.

3.2 Material specification

In Europe, weathering steel plates and rolled sections are produced in accordance with European Standard EN 10025-5 [33], and this should be used to specify the appropriate grades of weathering steel for use in bridges. Currently (2021) there is no European Standard for structural hollow section made of weathering steel, so national standards (such as BS 7668 [29] in the United Kingdom) have to be used.

Weathering steel gains its corrosion resistance from alloying elements, usually Copper, Chromium, Nickel, Molybdenum and Silicon. The total content of such alloys is between 1 % and 3 %. EN 10025-5 [33] also includes some grades with a comparatively high percentage (0.06 to 0.15 %) of phosphorus. But these increased phosphorus steels have a limited impact strength and are difficult or impossible to weld, therefore the authors of this European design guide recommend not to use such steel grades for the load bearing structure in bridge construction.

There are four general grades in EN 10025-5 [33]. In addition to the previous grades S235 and S355, there are now (since 2019) grades S420 and S460. The reduction of minimum yield strength with increasing thickness is the same as that for non-alloyed steel according to EN 10025-2 [30], so the same design rules for strength apply to both. Due to the new introduction of the higher strength grade S420 and S460, these are currently not covered by many national guidelines but already available in the market and used in impressive bridges as shown in Section 2.4.3.

There are up to five sub-grades related to impact toughness: J0, J2, K2, J4 and J5. These indicate, respectively, impact values of 27 Joules at 0°C, 27 Joules at -20°C, 40 Joules at -20°C, 27 Joules at -40°C and 27 Joules at -50°C. In bridge construction, a minimum subgrade of J2 for impact toughness is required for steel thicknesses t ≤ 30 mm. For thicknesses t > 30 mm a minimum of K2 is recommended, while J2 may also be allowed, if no national standards contradict or the maximum thickness according to EN 1993-1-10 [41] is not exceeded.

The designation is then completed with the letter “W” to indicate that the steel has improved atmospheric corrosion resistance. For the higher phosphorus steels, which are usually not suitable for bridges (see above) the letter “P” is also added. Finally, the symbol for the delivery condition is added with +AR for as rolled, +N to indicate normalised rolling or +M for thermomechanical rolling.

A typical example of the designation of a weathering steel grade suitable for use in bridges is therefore:

Steel EN 10025-5 Grade S355J2W+M

In versions prior to 2019, EN 10025-5 specified weathering steels whose characteristics other than chemistry were very close to conventional steels of EN 10025-2. Eurocode 3 in its 2005 version therefore treated steels from EN 10025 parts -2 and -5 in the same way.

However, there are now some differences other than chemistry between the weathering steels defined in part 5 of EN 10025:2019 [33] and the fine grain structural steels specified in parts 3 [31] and 4 [32] of the same standard, especially with regard to sub-grades. Table 3.1 shows the relationship between the grades and qualities of structural steels according to EN 10025:2019 parts -2 [30], -3 [31] and -4 [32] from 2019 and those of weathering steels according to EN 10025-5:2019 [33] with, where appropriate, additional requirements.

Table 3.1: **Correspondence between the characteristics of weathering steels according to EN 10025-5:2019 and conventional steels according to EN 10025-2/-3/-4:2019**

Structural steels		**Weathering steels**		
Standard	Grade, quality and delivery condition	Standard	Grade, quality and delivery condition	Additional requirements
EN 10025-2	S235J2 +N/+M*	EN 10025-5	S235J2W +N/+M	
	S355J2 +N/+M*		S355J2W +N/+M	
	S355K2 +N/+M*		S355K2W +N/+M	
	S460J2 +N/+M*		S460J2W +N/+M	
	S460K2 +N/+M*		S460K2W +N/+M	
EN 10025-3	S355N		S355K2W +N	- Guaranteed fine grain***
	S355NL		S355J5**W +N	
	S420N		S420K2W +N	- Impact test on longitudinal specimens taken in quarter thickness ****
	S420NL		S420J5**W +N	
	S460N		S460K2W +N	
	S460NL		S460J5**W +N	
EN 10025-4	S355M		S355K2W +M	- Guaranteed fine grain***
	S355ML		S355J5**W +M	
	S420M		S420K2W +M	- Impact test on longitudinal specimens taken in quarter thickness ****
	S420ML		S420J5**W +M	
	S460M		S460K2W +M	
	S460ML		S460J5**W +M	

* Delivery condition +M (thermomechanical) is not defined for Quatro plates in EN 10025-2:2019.

** J5 quality is not defined for long products in EN 10025-5:2019.

*** Producer's guarantee in accordance with Section 3.3 of EN 10025-3:2019 for steels in the normalized/normalizing rolled condition and Section 3.2 of EN 10025-4:2019 for thermomechanical steels. This guarantee must be indicated on the test document.

**** This impact test (impact bending) is performed in addition to the one specified in EN 10025-5:2019 and only for flat products of thickness ≥ 40mm. The test method is that defined in Section 10.2.2. of EN 10025-5:2019.

3.3 Allowance for the loss of thickness

Whilst significant continued rusting of weathering steel during the life of the bridge should not occur provided the environment and detailing is appropriate, some loss of material will occur. To account for this, it is assumed that each exposed surface rusts to a certain depth and a corresponding allowance for the loss of thickness has to be added. This thickness allowance should not be included in the calculation of the structural capacity, see Section 3.4.

The allowance for the loss of thickness can be varied depending on the local corrosion load (corrosivity) of the atmosphere. The typical corrosivity category in inland Europe today is C2 to C3 according to EN ISO 9223 [44]. The categories C4 and higher usually only occur in areas with high chlorides (e.g. marine atmosphere or as a result of de-icing salt), high levels of atmospheric pollution (e.g. sulphates) or permanent moisture. Various recent studies and measurement also show that the current atmosphere is getting cleaner and cleaner and that highly polluted environments (corrosivity category C4) only occur very rarely [22] [25]. The corrosivity categories are described in more detail in Section 2.3.2.

A polluted atmosphere is likely to increase the rate of continued rusting, and whilst this is often still low enough to allow the use of unpainted weathering steel, it may require a greater thickness allowance. Only few environmental conditions, such as very high concentrations of sulphates and chlorides, especially in marine atmospheres, can lead to the weathering steel being unusable (see Section 2.3.3).

All national guidelines mentioned in this document specify the allowance for the loss of thickness to be considered for rusting in more or less detail. In most of them they are based on the atmospheric corrosivity classification of the environment to which weathering steel is to be exposed, classified according to EN ISO 9223 [44].

Table 3.2 gives an overview of the allowances for the loss of thickness per exposed surface for a design life of 100 years given in the national guidelines including a recommendation of the authors of this European design guide.

Table 3.2: **Allowances for the loss of thickness for a design life of 100 years**

Country [Guideline]	Allowances for the loss of thickness related to corrosion classification in EN ISO 9223 [44]				
	C1	C2	C3	C4	C5
Belgium [2]	-	0.11 - 0.8	0.53 - 1.2	1.05 - 1.5	not allowed
Germany [3]	-	0.8	1.2	1.5	not allowed
United Kingdom [8] (for 120 years)	0.0	0.5	1.0	1.5	not allowed
France [1]	not applicable	1.0	1.0	1.0	not allowed
Spain [4] (exterior elements)	1.0	1.0	1.0	not allowed	not allowed
ECCS recommendation for bridges	**not applicable**	**0.8**	**1.0**	**1.5**	**not allowed**

The Belgian guideline [2] does not specify fixed values for the thickness allowances. On the one hand, it refers to a calculation method for the annual thickness reduction included in the ISO 9224 from 1992, which has been withdrawn and replaced in the meantime. On the other hand, the values of the German guideline [3] are given as an upper limit. These values refer to corrosion loads that are simply described as “low”, “medium” and “strong” but refer further to a predecessor document of the EN ISO 12944 [42].

The British guideline [8] refers its values directly to the atmospheric corrosion classification in EN ISO 9223 [44]. In the French guideline [1], the allowance of 1.0 mm per exposed surface is not intended as compensation for the loss of corrosion over the service life. It serves as a safety measure in case of strong corrosion or an unstable protective layer in an aggressive atmosphere, to give the client time to intervene, i.e. to paint the structure, at least partially. For structures located in a suitable environment, this allowance of steel is not intended to be consumed.

In Spain [4], the use of weathering steel is allowed up to corrosivity class C3 (medium corrosivity). In C4 or higher, marine atmospheres with high salinity or where the weathering steel is expected to be permanently wet, it is necessary to protect the surface, e.g. with a suitable paint.

Similar allowances for the loss of thickness should generally be made for fillet welds. As the size of butt welds is determined by the thickness of the connected plates, for which an allowance will already have been made, no further allowance is necessary. Normally no allowance need be made on surfaces that are not exposed, such as the interior surfaces of sealed box sections (sealed by use of continuous welding, gasketed manholes, or other means). Interior surfaces of ventilated box-sections should not be treated as "not exposed", but the allowance could reasonably be reduced to 0.5 mm.
A thickness allowance should not be applied to mechanical fasteners such as structural bolting assemblies or surfaces of weathering steel with an additional corrosion protection treatment according to the respective standards.

Initial indications from the latest studies [25] suggest that the current recommendations in Germany [3] are safe and the allowances for the loss of thickness may be reduced in the future as a result of reductions in atmospheric pollution due to structural change.

3.4 Design (Analysis)

Global Analysis

Since the global analysis is usually not particularly sensitive to the exact thickness of the steel sections, it may be carried out based on the cross-sectional areas and second moments of area appropriate either to the required design thicknesses after deduction of any allowances, or to the original gross thicknesses actually provided.

Detailed Design

Although it is unlikely that, at any given section and time during the life of the bridge, the entire exposed surface is rusted uniformly (to the thickness allowances given in section 3.3), the calculation of the stresses in and strengths of all sections, elements and connections should be based on the net size after deduction of a uniform thickness allowance.

3.5 Structural detailing

3.5.1 General principle

The first principle to be stated in detailing a weathering steel bridge is that normal good practice should be used. Most probably, a bridge whose details would not cause any problems in normal coated steel construction, and which is built in the appropriate environment, will also behave entirely satisfactorily in weathering steel. At the same time, most of the recommendations given here for weathering steel are also applicable to coated structures, as the durability of the coating or paint is otherwise not as long as expected.

However, to ensure that the weathering steel performs as intended and long-term durability is achieved, some aspects in detailing are particularly important:

3.5.2 Avoidance of permanent wetness or damp

A weathering steel bridge should not be permanently wet or damp. Hence, even if the general environment is satisfactory, it is important to ensure through good detailing that continual wetness does not occur at any point on the bridge steelwork. There are several ways in which this can be achieved, some of which are illustrated below.
Weathering steel bridges should be detailed to ensure the natural drying process for all parts of the steel structure by avoiding the accumulation of moisture and debris and ensuring adequate ventilation and drainage of water. This is absolutely necessary for the formation of the protective oxide layer on the surfaces of the weathering steel.
Typical precautions to avoid wetness are given in this Section.

Avoid details such as pockets, crevices or faying surfaces, which can collect and retain moisture (Fig. 3.1 to Fig. 3.4).
The shape and design of the stiffener must, for example, ensure adequate drainage. This can be provided by closed (triangular or trapezoidal) stiffeners or those with drainage passes with a minimum radius of 50 mm [8] (see Fig. 3.1).

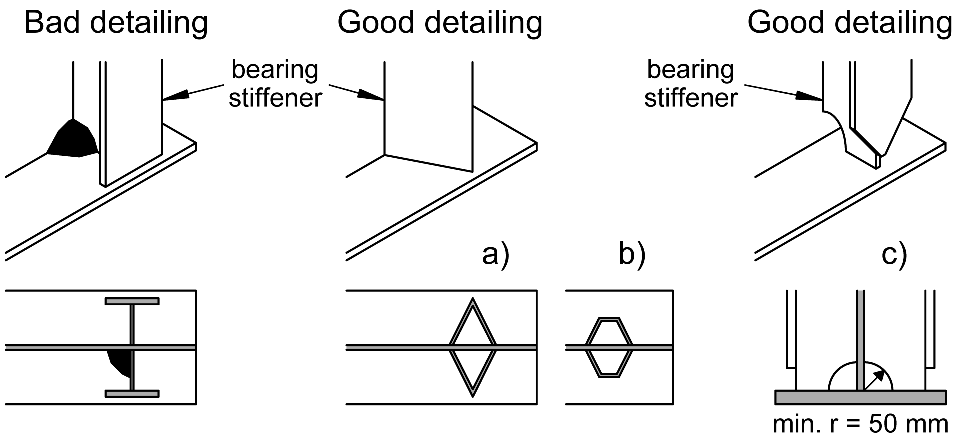


Fig. 3.1: Optimum choice of transverse bearing stiffener shape a) triangular stiffener, b) trapezoidal stiffener, c) drainage passes with a minimum cope radius of 50 mm

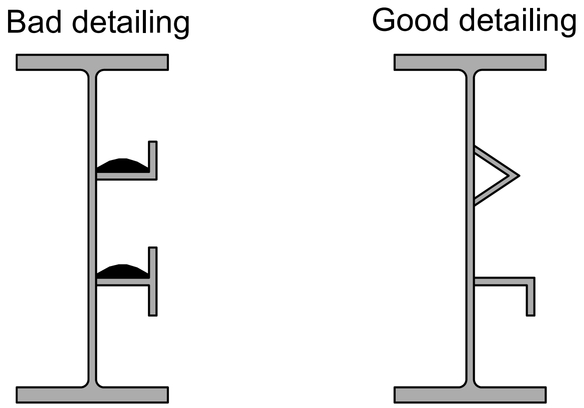


Fig. 3.2: Correct orientation of longitudinal stiffeners

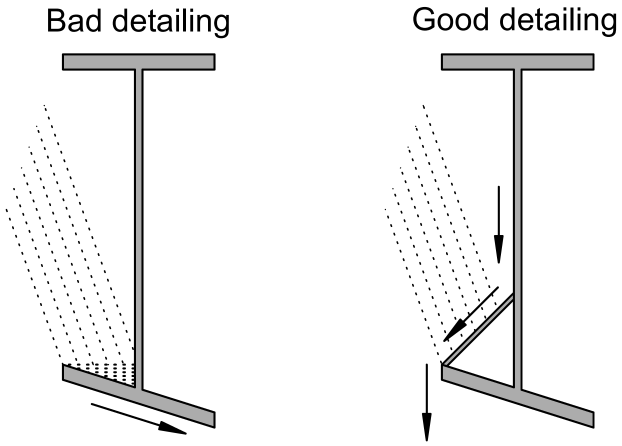


Fig. 3.3: Provision of run-off slopes on external (directly weathered) flanges

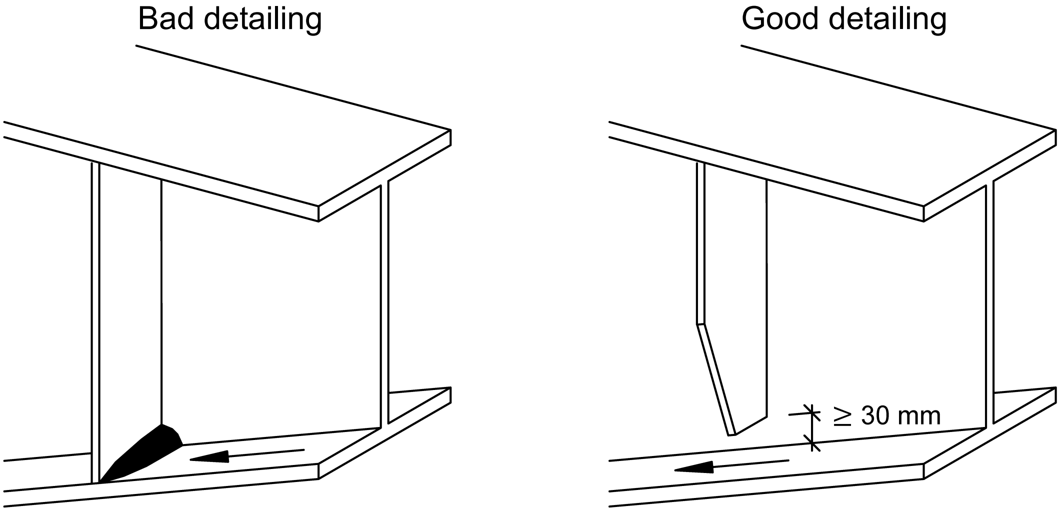


Fig. 3.4: Curtailing transverse web stiffeners to allow drainage below

Specify grinding flush of butt welds in profiles which may cause water traps, especially at the horizontal bottom flanges of I-beams (see Fig. 3.5).

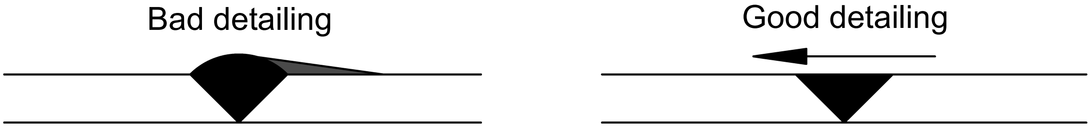


Fig. 3.5: Grinding flush of welds which otherwise form water traps

Avoid closely spaced girders to provide an adequate ventilation for drying (Fig. 3.6).

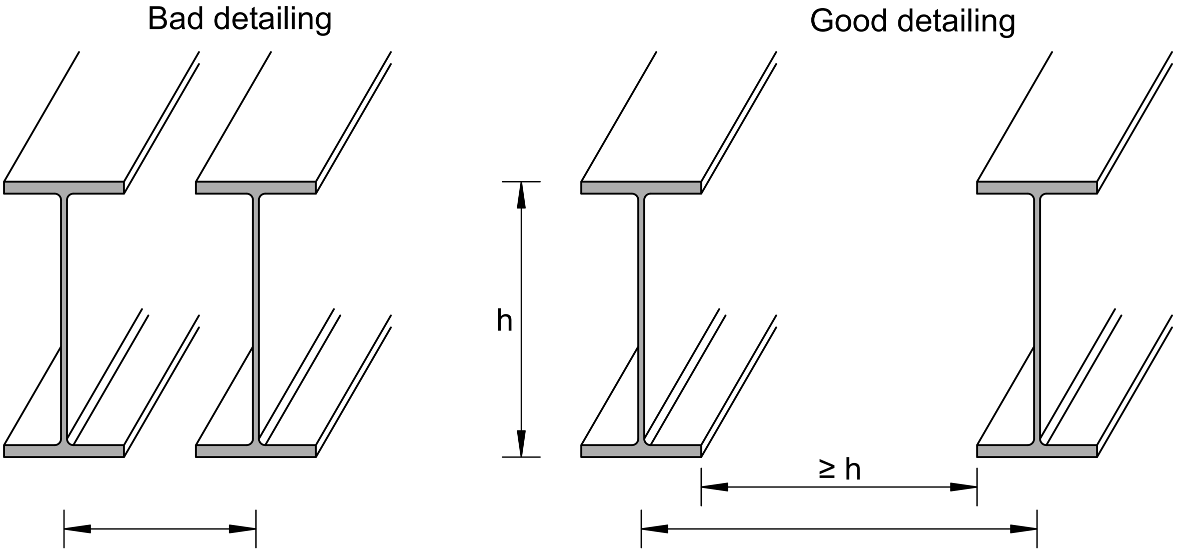


Fig. 3.6: Spacing of girders (recommended distance from [12])

Drip details must be provided at the caps or edges of concrete decks in composite weathering steel bridges (Fig. 3.7). If possible, the overhang of the bridge deck over the steel girder should be at least equal to the height of the girder to avoid direct wetting by rain. This also applies to the bridge caps of concrete decks in composite weathering steel bridges.

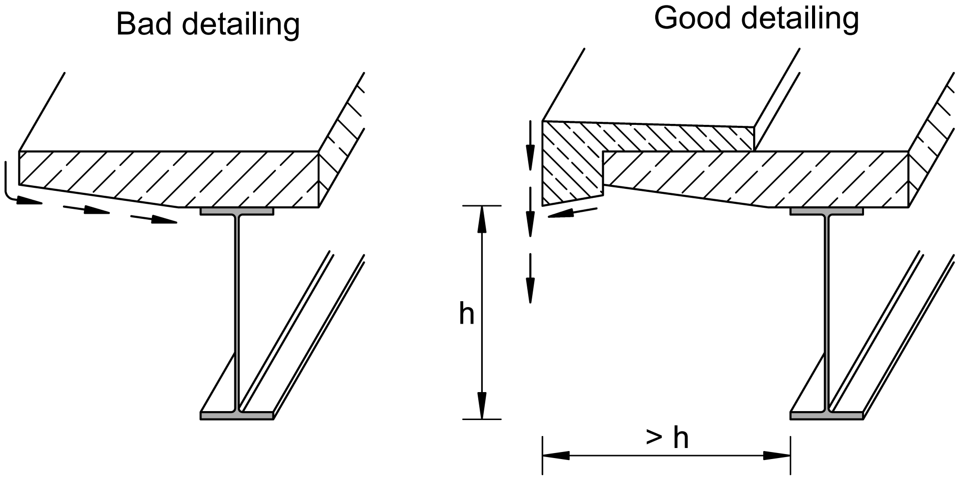


Fig. 3.7: Drip details at the caps or edges of concrete decks and overhang

The distance between the end of the girder and the retaining wall of the abutment should be at least 50 cm to ensure sufficient ventilation and drying (see Fig. 3.8). The end of the bridge deck should have a drip edge above the abutment, as the expansion joint above may leak. In addition, a drainage or rain gutter with an appropriate gradient should be planned under the expansion joint or at least a sloped abutment platform with a drainage gutter and pipes, as shown in Fig. 3.12.

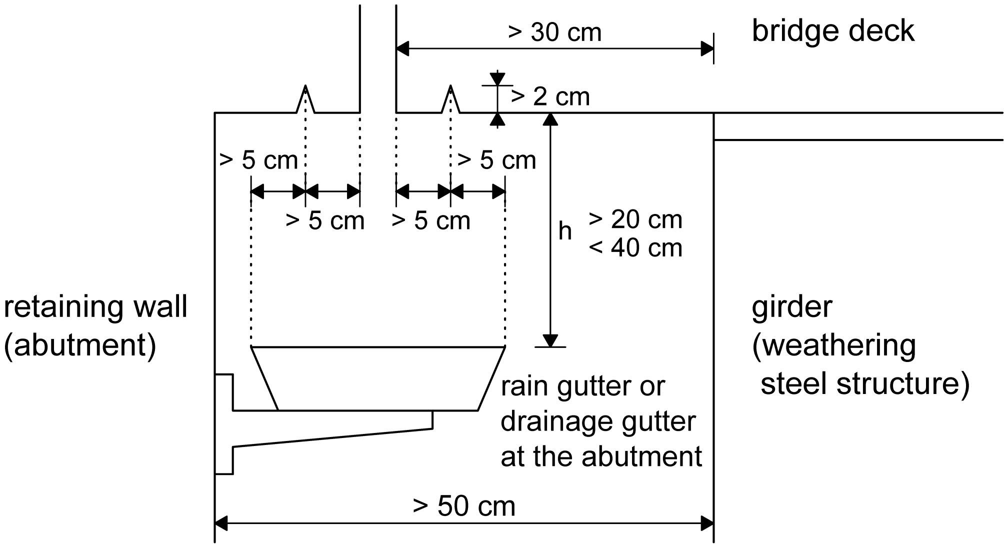


Fig. 3.8: Distances between the end of the girder and the abutment [1]

Ensure that lower flanges of box sections do not project horizontally, instead use extended web plates below their associated lower flange (including all welds) to form drip details (Fig. 3.9).

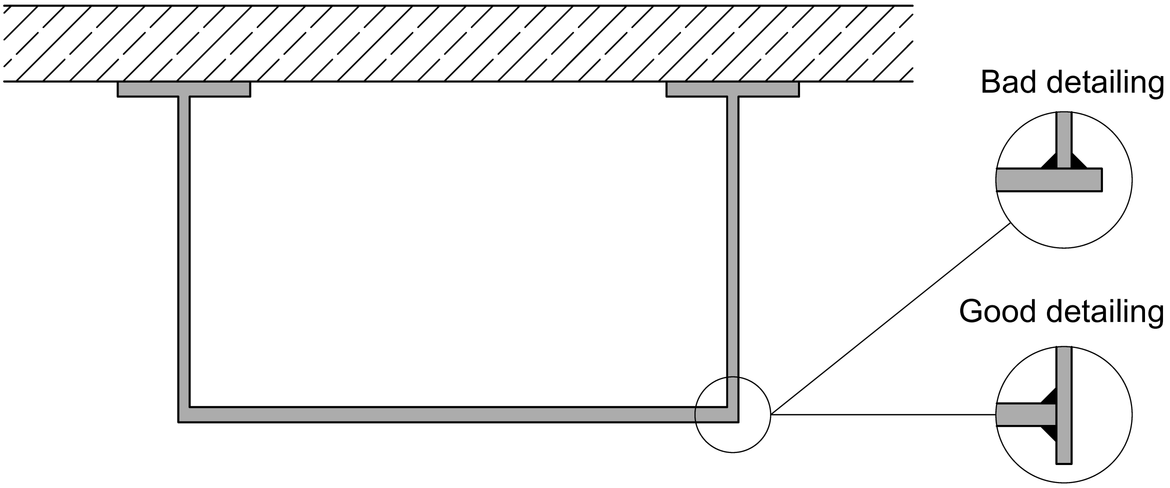


Fig. 3.9: Use of box sections

If (as is normal) a box section cannot be hermetically sealed, internal condensation will occur and adequate internal ventilation and drainage has to be provided. This should be observed especially for composite bridges with an unsealed concrete deck. To drain any water that may occur in a box girder, drainage runs of sufficient size through transverse diaphragms and internal transverse stiffeners should be provided [3]. Drainage downpipes routed through a box girder should be absolutely tight and air gaps between the box girder and the drainage structure should be avoided [3].

Wetting of the steel structure by water from (leaking) drainage pipes must be prevented. If there is a risk of blockage in the drainage pipes or drains due to leaves, rust or dirt, the smallest diameter of the drainage devices should not be less than 150 mm. Since drainage pipes do not always remain tight, especially at pipe joints and drainage openings, ensure that the pipes, pipe joints and cleaning openings have a sufficiently large distance from the steel structure. Condensation may also occur on drainage pipes. This has to be considered when routing uninsulated water pipes in box girders. [3]

3.5.3 Crevices

Crevices should be avoided. They can attract moisture by capillary action and can lead to local corrosion problems for bridges in uncoated weathering steel, because there is no coating or paint to seal them. Crevices can occur at any point where two surfaces are in contact and are particularly serious at overlapping bolted connections (see further comment on bolted connections in Section 3.7, including maximum bolt spacing for weathering steel). If a crevice is not adequately sealed, not only is water attracted without much chance of escape, but the resulting corrosion products have a higher volume than the original material and hence tend to distort or burst the connection. Furthermore, the corrosion products themselves will tend to attract further water and thus aggravate the situation. To avoid crevice corrosion at bolted connections, it is generally recommended to use preloaded bolts, even for non-structural connections, to ensure close contact [10].

In cross bracing between girders, use angles “flange upwards" (see Fig. 3.2) 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 Fig. 3.10).

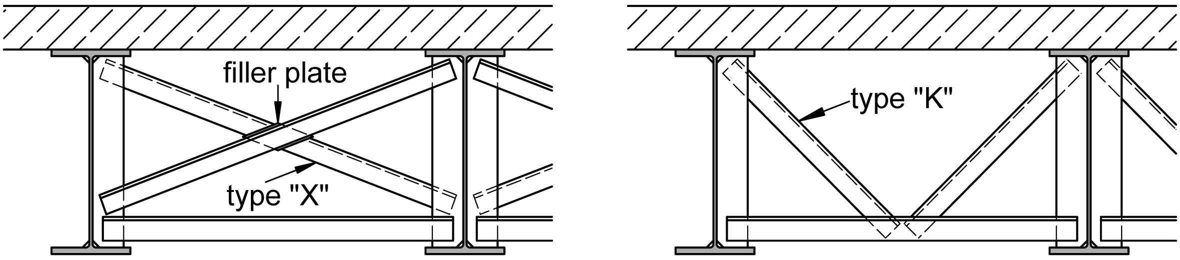


Fig. 3.10: Cross bracing details

3.5.4 Expansion and deck joints

The number of deck joints should be minimized, because leaking deck joints are one of the most common causes of serious problems in weathering steel bridges, allowing contaminated (usually saline) water to drop on to the steel below the deck. This can lead to permanent wetness and even attack an already formed oxide layer, especially if the chloride content is high due to de-icing salts. Therefore, bridge structures in which the deck runs continuously over intermediate piers or the deck is integrated with the abutments are particularly advantageous for weathering steel. The use of completely jointless bridges has been common practice in the USA for many years, and is now being encouraged in a number of European countries.

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 (see Fig. 3.8 or Fig. 3.12). Outlet pipes at the abutment should be 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 non-metallic type is preferable. Fig. 3.11 shows on the left an example of a damaged oxide layer (formed incorrectly). This damage is caused by a humid environment by dirt and water as a result of a leaking expansion joint combined with a badly or not planned drainage system at the abutment. On the right, an example of a local rehabilitation of a damaged area at another bridge (Mamer viaduct in Luxembourg) with a subsequent corrosion protection paint is given.

Fig. 3.11: (left) damaged oxide layer because of a leaking expansion joint and bad drainage system at the abutment and (right) a local rehabilitation of a damaged area with a subsequent corrosion protection paint

3.5.5 Run-off

Run-off water from the superstructure should not be permitted to run down the visible external surfaces of the substructure. It is liable to contain rust from the weathering process, and unless it is kept away from such surfaces will cause unsightly staining as shown in Fig. 3.17. The drainage of the deck and at piers and abutments requires careful design and detailing to ensure that this staining is avoided.

This usually means channelling any run-off water on the tops of piers or abutments and around bearings to drains that feed downpipes leading away from the pier or abutment. Avoid high-altitude free drainage gutter outlets by using downpipes. Refer to Fig. 3.12 and Fig. 3.13 for appropriate drainage of the abutment.

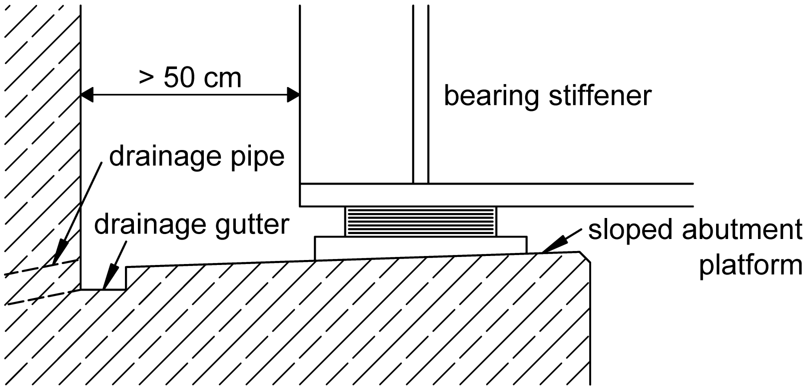


Fig. 3.12: Sloped abutment platform and drainage

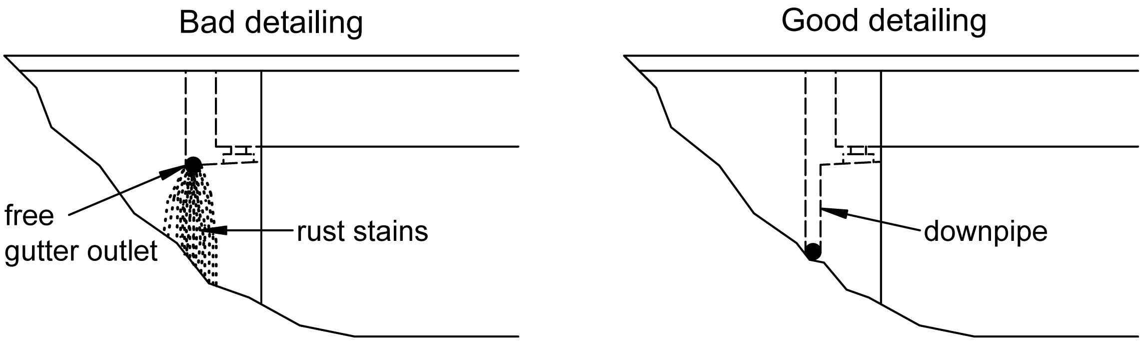


Fig. 3.13: Design of drainage to avoid rust stains

Particular care should also be taken to ensure that run-off from bottom flanges occurs away from piers. For this, drip plates can be used in the correct orientation, considering the slope of the bottom flange to avoid debris accumulation, as shown in Fig. 3.14. Instead of drip plates, welded seams or other suitable devices, such as glued PVC angles, can also be used as diversion strips, see Fig. 3.15 and Fig. 3.16. The use of drip plates or welded seams can reduce the fatigue strength of the bottom flange due to a lower detail category.

If there is any risk of water accumulation due to the geometry of the drip plates or welded seams, these should be removed or levelled.

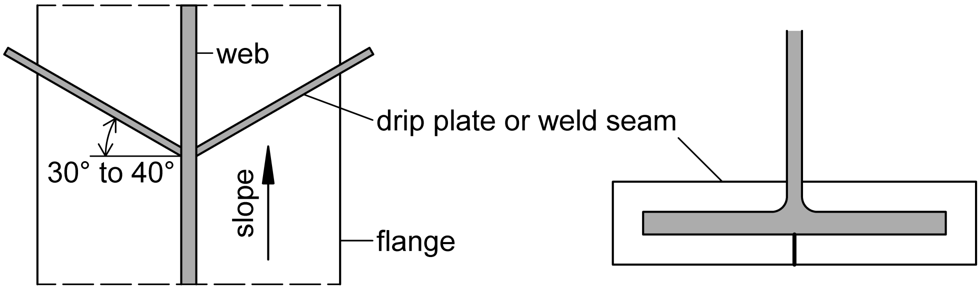


Fig. 3.14: Drip plate attached to bottom flange, sloped to prevent debris accumulation (Plan view on the left and in section on the right)

Fig. 3.15: Example of execution for welded seams as drip edges

Fig. 3.16: Example of welded seams as drip edges for an integral bridge without expansion joints

Fig. 3.17 shows examples for the appearance of an abutment with a good detailed drainage system without rust stains and a badly detailed one with serve rust staining.

Fig. 3.17: (left) Abutment free of rust as a result of a good detailing and drainage and (right) abutment with severe rust staining due to bad detailing

To protect piers from run-off, drainage gutters in combination with downpipes (Fig. 3.18) can be used instead of drip plates. It should be ensured that the downpipes are dimensioned and protected in such a way that they cannot freeze or become clogged. As an alternative, drip pans (Fig. 3.19) made of stainless steel can be planned as given or otherwise retrofitted by welding them to the bottom of the existing girder [7]. The drip pan must be designed so that the air can circulate around the weathering steel superstructure and bearing can be exchanged.

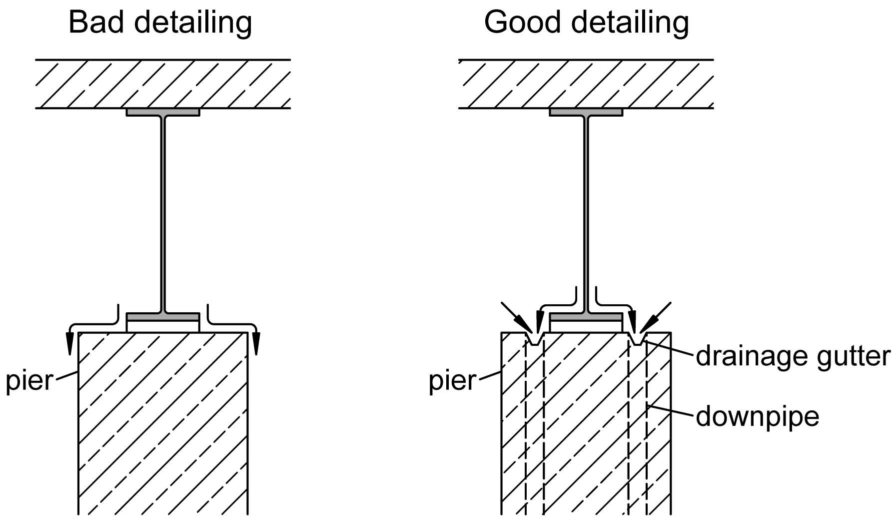


Fig. 3.18: Drainage gutter on the top of piers

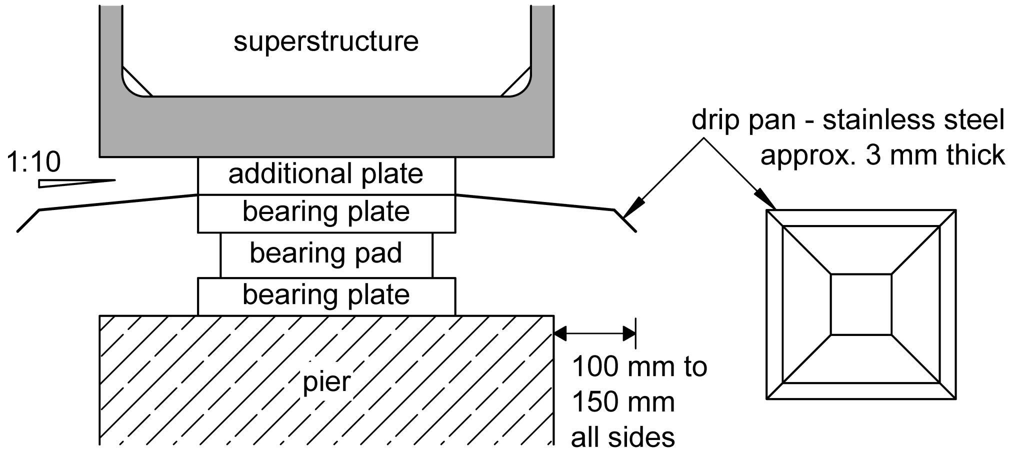


Fig. 3.19: Principle sketch for the design of a drip pan to protect piers from staining

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

3.6 Welded connections

Welding of weathering steels is – contrary to popular belief – not difficult. The design of welded joints for strength calls for no particular requirements above those of normal good practice except for the additional thickness allowance (see Table 3.2) on fillet welds. Full penetration butt welds do not normally require any additional corrosion allowance, because an allowance has been applied to the parent material thickness. Wherever possible, a designer should try to specify fillet welds which can be made in a single pass. This is because small single pass fillet welds normally permit the use of carbon steel electrodes, since there is usually sufficient pick-up of alloying elements from the parent material to give the weld matching weathering characteristics (some guidelines require special welding consumables also for single pass welds). With larger, multi-run welds it is necessary to use special electrodes, compatible with the parent steel, for the final (exposed) passes.
Further information on the weld procedure and consumables is given in Section 4.3.

One important aspect which should be noted is that all joints should be continuously welded on all sides to prevent moisture ingress and corrosion in the crevice formed by the contact surfaces. Fillet welds must be continuous (not intermittent) for the same reason. Some guidelines prescribe continuous welds mandatory for welded joints, in Germany [3] only for direct wetted joints and in Czech Republic [9] for every welded joint. Examples of good practice are given in Fig. 3.20.

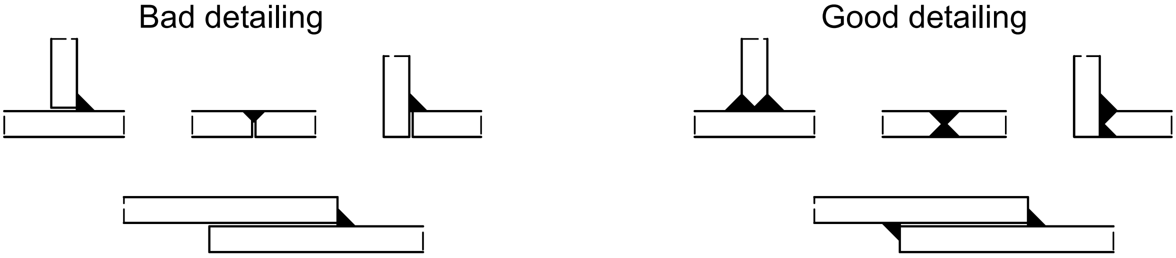


Fig. 3.20: Execution of welds

Weathering steels generally have a higher carbon equivalent value than most other high strength steels and consequently more pre-heat is normally required during welding. The usage of steels with the delivery condition +M (thermomechanical rolled) leads to lower carbon equivalents and may reduce this effect again.

Because of the extra care needed in selecting electrodes and the greater likelihood of needing preheat, site welding is sometimes considered a less attractive option than bolting for weathering steel. In addition, local grit blasting or grinding may be necessary after welding and the local appearance may differ from that of the rest of the steelwork, at least for the first few years. With care, however, the problems should prove relatively minor.

3.7 Bolted connections

3.7.1 Bolts

It is generally recommended to use preloaded bolts, even for non-structural connections, to ensure close contact and avoid crevice corrosion. Bolting assemblies with similar corrosion resistance properties to those of the plates and sections should be used.

While EN 14399-1 [37] does not give any specific information on preloaded bolting assemblies made of weathering grade steel, EN 1090-2 [36] contains some information (in its chapter 5.6.6). Accordingly, weather resistant assemblies shall be manufactured from a material with improved atmospheric corrosion resistance, of which the chemical composition shall be specified. Their mechanical properties, performance and delivery conditions shall comply with the requirements in EN 14399-1 [37] or EN 15048-1. Type 3 Grade A fasteners to ASTM standard A325 are given as suitable.

High strength structural bolting assemblies for preloading made from weathering steel are available from the United Kingdom, the United States and Japan. In the United Kingdom, high strength structural bolting assemblies for preloading of type HRC according to EN 14399-10 [38] are available in property class 10.9/10 and metric sizes with standard diameters M24 and M30. In the United States, weathering steel bolts are much more common in imperial sizes (with inch thread) and designated as type 3 according to ASTM F3125. Two strength grades are included in ASTM F3125, the grade A325 is equivalent to property class 8.8 and the higher strength grade A490 corresponds to property class 10.9.

Various sources [13] [16] [23] and practical experience have shown that hot-dip galvanised bolting assemblies can also be used for connections of weathering steel. Only during the formation of the protective oxide layer of the weathering steel in the first few years, the less noble zinc of the bolting assemblies is sacrificed in favour of the weathering steel, but this process ends when the protective oxide layer has formed as an insulating layer. The zinc layer must be thick enough to endure the limited initial time of galvanic attack up to this point.

As an alternative, preloaded bolting assemblies made of stainless steel can also be used without problems of bimetallic corrosion, as described in Section 3.9.

Under the very favourable dry environmental conditions in Italy, ordinary “black” bolting assemblies are also often used successfully for connections of weathering steel. Long-term experience from structural maintenance checks show no significant signs of corrosion in unprotected preloaded bolted assemblies outside particularly aggressive environments. In terms of the alloying elements, the steel of the high strength structural bolting assemblies can be considered to be “higher alloyed” than the weathering steel of the structure. This suggests that the uncoated bolts have sufficient resistance to atmospheric corrosion under the mostly favourable dry and warm environmental conditions of Italy. [20]

3.7.2 Slip factor of contact surfaces in slip resistant connection

The slip factor of blast cleaned weathering steel is not different from that of blast cleaned ordinary carbon or carbon/manganese structural steel. Furthermore, the development of a firmly adhering protective oxide layer, such as that produced by wetting and drying for several months by non-polluted water, does not degrade the slip factor. Research [25] has confirmed that friction surfaces blasted with shot or grit according to class A of EN 1090-2 [36] even with subsequent weathering for several months prior to assembly still have a slip factor of $\mu = 0.50$. The friction surfaces of the specimens were weathered for four months in contemporary urban or rural atmosphere (C2 without a pollution by chlorides) before assembly. They remained load-bearing even under cyclic loading and no reduction of the slip factor is necessary.

Fig. 3.21: Slip resistant connection with preloaded weathering steel bolts and an alkali-zinc-silicate paint on the contact surfaces at the Howald bridge in Luxembourg

Loose rust or mill scale would affect the slip factor, but must be removed anyway to ensure that an even protective oxide layer can form (see Section 4.4).

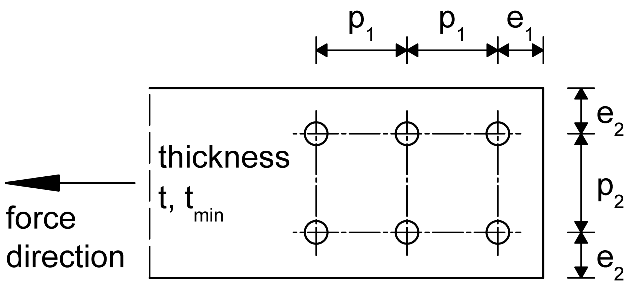
In some national guidelines (Belgium [2] or Germany [3]), in addition to the special bolt spacing according to EN 1993-1-8 [39] for joints made of weathering steel (see the following Section), a painting of the friction surfaces is required to avoid crevice corrosion. For a blasted friction surface painted with an alkali-zinc silicate paint, a slip factor of $\mu = 0.40$ can be applied in accordance with EN 1090-2 [36]. This surface preparation was used for example for the on-site connections of the Howald bridge as shown in Fig. 3.21 and the Syre viaduct mentioned in Section 2.4.1.

3.7.3 Crevice corrosion and bolt spacing

Emphasis on the avoidance of crevices has already been mentioned. Bolted joints inevitably contain crevices. But provided the surfaces are held together in sufficiently close contact it has been found that problems do not arise. Close contact requires the use of preloaded bolts, such as high strength structural bolting assemblies as described in Section 3.7.1, and good dimensional accuracy in steel parts. Further, joining very thick plates with small diameter bolts and low preload should be avoided.

However, it must be recognised that any flexing in service of the connected steel members can open the joint and lead to the ingress of moisture as a result of capillary action. Hence more stringent requirements on bolt centres and edge distances are required compared to joints in painted non-alloyed structural steel. The European code EN 1993-1-8 [39] contains the following limit values for steel structures made of unpainted weathering steel (conforming to EN 10025-5 [33]), also shown in Fig. 3.22:

- The distance from the centre of any bolt to the nearest free edge of a plate in longitudinal and lateral direction of force should not exceed the larger value of eight times the thinnest outer component ($8 \cdot t$) or 125 mm.
- Bolt spacings in lines adjacent to plate/section edges should not exceed fourteen times the thickness of the thinnest component ($14 \cdot t_{min}$), and in any case should not exceed 175 mm.



e_1 and $e_2 \leq$ max. [$8 \cdot t$; 125 mm]

p_1 and $p_2 \leq$ min. [$14 \cdot t_{min}$; 175 mm]

Fig. 3.22: Maximum hole and edge distances according to EN 1993-1-8 [39]

If these limitations cannot be met for any reason, either the joint must be protected by a suitable paint or a suitable sealant should be applied around the edge of the joint.

3.7.4 Corrosion allowance for bolts

There are no specific code requirements for any corrosion allowance to be made on the size of bolts. It is reasonable to assume that in a properly detailed bolted connection the bolt shank may be treated as "not exposed" and hence no thickness allowance has 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 nut), a suitable local sealing or paint is likely to be the preferred treatment, since continued wetness could cause corrosion far in excess of any nominal allowance.

3.8 Fatigue

Sometimes concern is expressed that weathering steel bridges may exhibit worse fatigue performance than those in ordinary structural steel. This view comes from the fact that corrosion forms pits from which fatigue cracks might initiate earlier, 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, a general consensus can be found. As described below, corrosion causes a slight decrease in the fatigue strength of the plain section or sheet of weathering steel, but no reduction is required for the welded or bolted joints that are almost always decisive for the fatigue design:

(a) After the weathering process has occurred, plain weathering steel (i.e. components which have not been welded or fabricated in any way), will have a slightly lower fatigue strength than plain uncorroded steel. For this reason, according to EN 1993-1-9 [40], the next lower detail category should be used for plain products made of weathering steel. However, this only concerns the detail categories 160 for rolled and extruded products as well as 140 or 125 for sheared or thermally cut plates (EN 1993-1-9 [40], table 8.1, constructional details 1 to 5).

(b) Fatigue failures in bridges are almost always initiated at a point of geometrical discontinuity or stress concentration such as a welded or bolted connection: this gives a much greater reduction below the plain steel fatigue strength than the presence of corrosion pits in weathering steel does. It appears that, provided the category to Eurocode 3-1-9 [40] of the critical detail is 112 or lower, the use of weathering steel will not cause any reduction of fatigue life. Even if the detail is category 125, no reduction is required because of to the weld (but, if used, perhaps because of thermally cut plates with category 125, see (a)).

(c) Tests which show worse behaviour of low category joints have 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 and the results of such tests may therefore be considered inappropriate and disregarded. However, they also show that it is essential to follow the guidelines on suitable environments given in Section 2.3.

Even though welded weathering steel bridges have no lower fatigue performance than those from coated or painted steel, it is desirable to design the details to be as fatigue-resistant as possible. As will be described in Section 5.6, fatigue cracks in structures in uncoated weathering steel are harder to detect than those in coated or painted structures.

3.9 Connection to other materials

In general, any connection to a more or less noble metal runs the risk of corrosion of either the weathering steel or the less noble material. However, such corrosion will only occur in the presence of an electrolyte (such as water) and depends on the type of the connection as well as the mass ratio of the materials. It has been found that a connection between weathering steel and hot-dip galvanised components (for example hot-dip galvanized bolts) can work, provided the zinc layer is thick enough to allow an initial sacrificial erosion until the protective oxide layer has formed on the weathering steel [13] [16] [23].

Care should also be taken when unpainted weathering steel and stainless steel (for example in bearings) are connected without electrical insulation, as in this case the weathering steel would be sacrificial. However, experience has shown that provided the joined area does not act as a crevice to attract water, serious problems are unlikely to arise. Due to the significantly smaller mass, bolting assemblies made of stainless steel, for example, are not critical for the corrosion of the weathering steel and can be used. Fig. 3.23 shows a connection of A4 stainless steel bolts with weathering steel without any evidence of galvanic corrosion 12 years after erection.

Fig. 3.23: A4 stainless steel bolts at a footbridge made of weathering steel after 12 years in service

Apart from the consideration of the potential problems of galvanic action if weathering steel is connected to other metals, staining of other materials by rust-laden water running off the bridge is another issue of compatibility which should be considered during the design stage. The questions of whether and how to clean the stained material and how staining can be prevented is answered in the following Section 3.10.

3.10 Removal of rust stains

Although rust staining should not occur on a well-designed and well-drained bridge or its substructure, the designer should still be aware of the behaviour of various materials when stained. The sensitivity of an adjacent material to staining and dirt is mainly dependent on its surface condition [3]. If possible, use those that can be easily cleaned. Of those materials in common use in bridges and their substructures, the following are subject to minimal staining and can generally be cleaned relatively easily:

- Ceramic tile and glazed brick
- Washable air-drying and thermosetting organic coatings (paints)
- Stainless steels
- Aluminium, anodised and non-anodised

The following materials are prone to severe staining and are difficult or impossible to clean:

- Concrete and stucco
- Galvanised steel
- Unglazed brick
- Stone
- Wood

When detailing, particular care should therefore be taken to ensure that rust-laden water will not come into contact with such materials.

An example of the staining which can result from run-off onto concrete compared to a better detailed example is shown in Fig. 3.17.

3.11 Further protection – initial painting

There is no reason why the whole bridge surface should be painted. However, there are some weathering steel bridges in existence where the designer wished to provide further protection from the outset. Painting the steelwork has been specified in areas where it was assumed that the environment would prevent the formation of the protective oxide layer. This can occur with long-term to permanent wetness of surfaces, particularly in conjunction with high chloride exposure (e.g. from de-icing salt water or in maritime environments) or due to the accumulation of debris, salt, or other contaminants. Such areas include the top surfaces of bottom flanges, perhaps together with some of the bottom of the web, and areas below expansion joints.

In such circumstances, the same high-protective paint systems as used for non-alloyed structural steel may normally be specified. There is some evidence that, although the paint itself lasts no longer than on ordinary structural steel, if it is damaged or degraded the self-healing properties of the rust which is formed helps to prevent under-creep. This can be beneficial since damaged areas which require touch-up and repainting 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 painting. The colour of the paint on exposed steelwork should be selected to match the expected colour of the steel after a few years of weathering. The surface to be painted must first be prepared according to the standards, similar to non-alloy structural steel. Subsequent painting of surfaces that have already been exposed, for example as a rehabilitation in the case of unexpected heavy corrosion, is also possible if the existing oxide layer has been removed beforehand in accordance with the standards, as explained in more detail in Section 7.3.

4 FABRICATION AND ERECTION

4.1 Cold and hot forming

Weathering steel can be cold formed as any comparable structural steel according to EN 10025. In case of higher cold forming ratios, i.e. edging on mechanical presses, it is advisable to consult the steel manufacturer prior to placing the order. As for other steel grades, cold forming will lead to a reduction in toughness which has to be considered when designing (e.g. EN 1993-1-10 [41]). Flanging is generally not recommended according to EN 10025-5 [33] for structural shapes or for plates and bars with a thickness over approximately 20 mm. Furthermore, the steel grades and qualities suitable for cold forming as well as the respective recommended minimum cold bending radii for bending without cracking are specified for plate thicknesses up to 20 mm.

The heating process involved in hot forming can affect both tensile properties and notch toughness, particularly in steels without sufficient grain refining elements. Only products ordered and supplied in the normalised or normalised rolled condition can withstand some heat treatment or hot forming processes and must still exhibit the mechanical properties as supplied after hot forming [33] and repeated normalising. According to EN 10025-5 [33], products ordered and delivered in the thermomechanical rolled or as-rolled condition are not suitable for hot forming (e.g. at ~900°C).

Recommendations regarding hot forming, cold forming and flame straightening are given in CEN/TR 10347.

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 structural 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. In this respect the preheat conditions must be adapted to the increased carbon equivalent of weathering steel. Flame-cut edges left untreated will affect the formation of the protective oxide layer. Therefore, it is recommended to grind the hardened edges [7].

4.3 Weld procedure and consumables

Weathering steel can be welded using many common welding processes known from non-alloyed structural steel.

Weathering steels, because of their relatively high carbon equivalent values, may require rather more preheat before welding than most other structural steels. Thermomechanical rolling offers a good option to lower the carbon equivalent for weathering steels and therefore improves the weldability. In addition, before welding, any already formed oxide layer should be removed at a distance of 10 mm to 20 mm from the welding edge [33]. Apart from that, procedures are generally similar to non-alloyed steels.

Welds must be made in accordance with EN 1090-2 [36] and EN 1011-2 [34]. There is a wide range of electrodes with properties compatible with the parent weathering steel as indicated in Table 4.1 according to EN 1090-2 Table 6 [36].

It is normally not necessary to use electrodes with compatible weathering properties for small single pass welds, or for internal runs of multi-run welds. In the case of single pass welds, sufficient absorption of alloying elements from the base steel will give the weld metal a corrosion resistance and colouring similar to the base. For multi-run welds, there is no need for the internal runs to have such resistance, provided the capping runs as well as the heads of the internal runs in butt welds are made using suitable consumables. It is, of course, essential that electrodes with adequate mechanical properties are chosen.

Suitable weathering welding filler wires are available from several suppliers (among others Esab, Lincoln Electric, S.A.F. Air Liquide and Thyssen).

Table 4.1: **Welding consumables to be used with steels according to EN 10025-5 [26] [36]**

Process	**No.**	**Option 1**	**Option 2**	**Option 3**
Shielded metal arc welding (SMAW)	111	Matching	2.5 % Ni	1 % Ni, 0.5 % Mo
Submerged arc welding (SAW)	121, 122	Matching	2 % Ni	1 % Ni, 0.5 % Mo
Gas metal arc welding (GMAW)	135	Matching	2.5 % Ni	1 % Ni, 0.5 % Mo
Flux-cored arc welding (FCAW)	136	Matching	2.5 % Ni	1 % Ni, 0.5 % Mo
Matching: 0.5 % Cu and other alloy elements				

Welding of different weathering steel grades to each other is possible and permissible. Weathering steel can also be welded to other weldable, non-weather-resistant structural steels like non-alloyed structural steel. In this case, the weld seam zones as well as the adjacent components made of non-weathering steel must be protected according to their corrosion load. [1] [3]

4.4 Surface preparation

It is important that all contaminants are removed from the surface of the weathering steel to enable it to form its protective oxide layer. Mill scale will be undercut during the weathering process and will fall off eventually, but this delays the formation of a uniform coloured protective oxide layer, so it is necessary to remove it. Removal of mill scale and contaminants can be achieved by an all-over post fabrication blast clean with non-metallic shot or grit abrasives to a standard equivalent to class Sa 2.5 “very thorough blast cleaning” according to EN ISO 8501-1 [43]. In this process, mill scale, rust, paints and foreign matter are largely removed and the remaining residues must adhere firmly. At some steel producers, weathering steel can also be ordered already shot blasted out of the fabrication.

In addition, a surface preparation could be required for the contact surface of a slip-resistant connections made with preloaded bolts to achieve reliable (high) slip factors, as explained in more detail in Section 3.7.2.

4.5 Handling, storage and erection

The use of metal slings for handling should be carefully controlled since they can damage the developing protective oxide layer on the steel. This will develop again, but could result in an uneven appearance until then.

Contamination of the surface should be avoided. This may arise from concrete, mortar, asphalt, paint, oil or grease. Marking the surface with wax crayons should be avoided, since the marking can be very difficult to remove.

Storage of weathering steel sections and plates should ensure that the protective layer continues to develop. This means that in ideal conditions they will be stored such that they are alternately wetted by clean rain and dried. Long-term storage in areas with high chloride contamination, for example by (de-icing) salt water spray, should be avoided. Unless they are stored inside, 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 sags 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.

During erection, the main precaution should be to continue to protect the sections from contamination and damage. Site welded joints may require special treatment, such as grinding off excess weld on the upper surfaces of flanges to avoid potential corrosion traps, and 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, by brushing or, if not otherwise possible, by a site blast clean. Similarly, areas where severe physical damage has occurred may also require blast cleaning after any repair (such as 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 tears until the final construction inspection is made.

To prevent rust stains, follow the structural detailing given in Section 3.5. However, if rust stains should occur during construction or in the further lifetime of the bridge, they may be removed by abrasive blasting or with a commercial cleaning solution.

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 avoid trouble at the first opportunity. A weathering steel bridge that is properly designed, detailed and in the correct environment should not cause any trouble. However, it is necessary to inspect it to ensure that specific problems to which weathering steel bridges are occasionally prone are detected as soon as possible to enable a satisfactory permanent solution to be found.

Inspection is required to ensure that a good protective oxide layer has been formed and is not flaking off, that moisture and detritus are not collecting and that the thickness of the structural elements can be verified by measurements. A monitoring programme 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.

As an example, crevice corrosion could cause structural damage, if it progresses unchecked. However, if detected in time, a simple and satisfactory remedy can usually be found. In principle, bridges made of weathering steel do not require more inspection than bridges made of other materials, such as painted non-alloyed steel. Only slightly different details regarding the surface and corrosion come into focus.

5.2 Routine inspection

There are no uniform European specifications for the surveillance and inspection of bridges. Each bridge owner determines for himself whether and at what intervals detailed bridge inspections must be carried out and the scope of these inspections. In addition, many countries still have regular visual inspections at shorter intervals (e.g. once a year). Besides the aspects of detailed bridge inspection (e.g. every 5-6 years) described in Section 5.3, the special properties and behaviour of weathering steel give rise to a number of questions to be answered during each routine visual inspection of a bridge:

- Is there dirt or debris lying on the bridge structure or vegetation near to it, which could cause any part of it to remain permanently wet?
- Has the surface been contaminated by retained pollution, graffiti, or other material?

- Are all expansion joints performing satisfactorily? If water is coming through them is it running on to any part of the bridge or is it being adequately drained?
- Is there evidence of water collecting and remaining at any point of the bridge?
- Are there any significant local changes in the appearance of the oxide layer that could indicate a leaking drainage system or other causes of permanent moisture?

5.3 Detailed inspection

Provided that provision has been made for it in design, the routine visual inspection described in Section 5.2 should not pose any particular difficulties. However, the detailed inspection of weathering steel bridges differs in a number of respects from the inspection of coated or painted bridges and might be more difficult in general. Nevertheless, any competent steelwork inspector can be trained to look for the appropriate aspects.

One of the advantages of weathering steel is that the surface can be seen directly. However, whilst a seriously corroded surface will be obvious, an inspector must be familiar with the various colours, textures and general appearance that the protective oxide layer may take on when exposed to different environments in order to judge whether or not the oxide layer has the intended protective properties. Furthermore, visual appearance on its own may be deceptive, and mechanical or other tests may be necessary to determine whether or not the oxide layer adheres to the underlying steel base.

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

Depending on the chosen safety concept in the fatigue design with corresponding partial safety factor according to EN 1993-1-9:2005 [40], more or less intensive frequent inspections are required. As described in Section 5.6, detection of fatigue cracks in weathering steel bridges can be more difficult than detection of cracks in coated or painted steel.

Critical areas that should be specifically checked for their functionality, load-bearing capacity and durability during a detailed bridge inspection include (especially from [8] and complemented):

- Areas near “fixed” and “expansion” joints
- Steel structures near or adjacent to drainage pipes

- Near flat surfaces or corners of steel structures
- Steel structures in the vicinity of drainage culverts through stiffeners
- Steel structures adjacent to drainage details (e.g. drip edges or plates)
- Welded details
- Bolted joints (especially with regard to crevice corrosion and loose bolts)
- Seals along interfaces between concrete and weathering steel

5.4 Surface appearance

An inspector must be able to distinguish between a protective and a nonprotective oxide layer. Normally this can only be done at close range (within 1 m distance). The appearance will give the first indication of the quality of the protective layer. Whilst only experience can make an inspector an expert in such matters, some guidance is given below.

In colour the protective oxide layer should begin as yellow orange after the initial stage of exposure, then become light brown, and finally chocolate to dark brown. In some lighting conditions it can appear metallic grey to purple. See Fig. 5.1 for an example of a very young oxide layer during erection and a fully formed protective oxide layer after many years in service. A black layer is normally nonprotective.

Fig. 5.1: Example for a very young oxide layer while erection (left) and a fully formed oxide layer after many years in service (right)

In texture, the protective oxide layer should be tightly adhering 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 normal in the early stages of exposure, but should change after a few

years. The surface should be as fine-grained and uniform as possible, a grainy or flaky appearance are danger signs. For example, an average grain size of more than 5 mm can be an indication of an improperly performing protective layer [1].
The overall evaluation considers the general appearance of the oxide layer, individual deviating areas should be evaluated separately. As part of the overall evaluation, the appearance of the patina could be recorded in the form of photographs (Fig. 5.2), on which a colorimetric reference could appear to allow the colour evolution of the patina to be followed from one inspection to the next. A millimetre scale is also useful to allow the evaluation of the grain size of the patina.

Fig. 5.2: Different appearances of the oxide layer recorded by photographs

The timing of the colour and texture changes can vary with atmospheric conditions. A rural, unpolluted atmosphere will result in the light colour and dusty texture taking significantly longer to change. The steel composition can also affect this, the greater the extent of alloying elements, the darker the final colour.
If the condition cannot be reliably ascertained, it may be necessary to blast off part of the protective layer to determine the extent of pitting and to measure the section loss. Equipment is available which enables measurements of section loss to be carried out without totally removing the surface layer (see the following Section 5.5).

5.5 Measuring of steel thickness

In addition to the inspection of the surface appearance of weathering steel, the remaining steel thickness should also be measured in defined time intervals and at previously determined reference points of the structure. The measurements in service can be carried out for example with ultrasonic test systems. For any measurements of steel thickness in service to be of value, it is necessary to have an accurate record of the initial thickness measured at the time of fabrication using callipers or other equipment, like ultrasonic test systems. The reference points for future measuring in the same locations should be defined on the as-built drawings or in the bridge maintenance manual and, if necessary, permanently marked directly on the structure. Measuring internal surfaces is quite impossible using mechanical means.

Specialist portable ultrasonic equipment is available and established to enable residual thickness measurement to be obtained without the need to remove the adherent protective oxide layer. A residual thickness survey can be undertaken by one person using a hand-held measuring probe connected by cable to a pocket-sized instrument. Additional facilities include a small data logger programmed to store all measured values, which in turn can be downloaded and processed by a computer.

To obtain a representative overview of the steel thicknesses of the whole structure, measurements should be carried out in different locations. These include those that are critical or sensitive to:

1) Strength and high stresses
2) Differences in exposure (e.g. direct or indirect weathering)
3) Debris accumulation, persistent wetness or condensation
4) Susceptibility to joint or drainage leakage

Subsequent measurements in the same initial measured locations provide an opportunity to establish corrosion rates over a long period of time without the need to remove the protective oxide layer [1].

The thickness of the oxide layer alone can be measured with common layer thickness gauges. These thickness measurements are not completely exact, as the roughness of the oxide layer is also considered, but they give a very good indication. It is essential to note that the measured thickness of the oxide layer does not correspond to the actual removal of the base material. On the one hand, the oxide layer has a significantly larger volume as a result of the chemical corrosion processes and, on the other hand, the outermost layer will continuously be slightly eroded as a result of the exposure to natural weathering.

5.6 Detection of fatigue cracks

In a painted steel bridge, the first indication of a fatigue crack is often the colour contrast between the paint and the rust stain in the vicinity of the crack. Such obvious signs would, of course, be absent in weathering steels. Indeed, observations of crack growth in fatigue tests of weathering steel beams have shown that fatigue cracks less than 150 mm 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.

If a crack is suspected it can probably be confirmed (or otherwise) using magnetic particle inspection methods: this, however, requires preparation of the surface first.

Recent investigations [25] have shown that the electromagnetic acoustic transducer (EMAT) can be a practical ultrasonic testing method for non-destructive crack detection and can be successfully applied to steel structures without painting, as with unpainted weathering steel, even with a protective oxide layer. Cracks and scratches on flat surfaces can be detected from a depth of 0.3 mm.

In Czech Republic, the magnetic metal memory method (MMM method) is used for the detection of fatigue cracks. This method also works with corrosion layers, as it searches for the magnetic peaks that occur at stress concentration zones due to fatigue cracks.

6 MAINTENANCE

6.1 General

Routine maintenance of weathering steel bridges primarily consists 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 in Section 7 Rehabilitation of weathering steel bridges.

Highway bridges, by their nature and use, accumulate much 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 oxide layer and, for the continued satisfactory performance of the bridge, maintenance must be directed to prevent or remedy 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 non-adherent or poorly adhering sheets 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 leaking joints.
- Clean drains and downpipes and check their functionality, so that no water can get to the steel construction, even in windy environment.
- Remove vegetation from the vicinity of the bridge.
- If necessary, install new drainage systems to divert water from super- and substructure.
- In the event of “pack-out” rust at bolted joints caused by crevice corrosion, the edges of the joint should be sealed with a suitable sealant (for further information see Section 7.2).

6.3 Graffiti removal

As with other unpainted structures, such as reinforced or prestressed concrete, graffiti removal from weathering steel bridges is difficult. Therefore, measures to prevent public access to the girders and other structural elements should be considered first. However, this should be balanced with the need to allow access for inspection, monitoring and cleaning.
The following methods can be considered to address the problem with graffiti:

- Prevent public access to the weathering steel construction through protective measures.
- Trials have shown that the use of chemical paint softeners followed by steam or hot water cleaning is the most suitable method for the removal of graffiti from weathering steel. It causes only very little damage to the protective oxide layer and minimal local changes to surface appearance. [24]
- Leave the graffiti if not objectionable, as it will eventually be absorbed into the oxide layer as it forms.

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 designer arise (for example a new industrial complex causing severe pollution is built close by). However, there are a few existing weathering steel bridges where performance has been less than ideal, probably because some of the guidelines were not existing or 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 normally involves sealing of crevices, blast cleaning and painting of the excessively 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 main reasons for section loss, the rehabilitation of such areas is an important procedure. Crevices can be treated by one or a combination of the following methods, depending on the type of detail and the degree of corrosion:

- Disassemble the detail containing the crevice (for example a bolted joint), blast clean the contact surface to the required preparation grade, apply a suitable paint and reassemble. Note that, if the detail is a slip resistant connection, painting of the contact surfaces would only be acceptable, if an adequate slip factor can be shown to be attained.
- If the connection cannot be disassembled but the load-bearing capacity is still given, first remove all corrosion products by manual or mechanical cleaning of the surfaces and joints. Then apply a primer to the cleaned surface of the whole joint lapping 200 mm in the surrounding steelwork, seal the joint with a suitable moisture-cured sealant and finally cover the joint including the sealant with a suitable top painting. [12]

- Inject the crevice with a suitable epoxy compound and then caulk all edges with epoxy.
- Seal weld all edges, but not those of bolted joints. Make sure that no fatigue issues occur due to subsequent welding.

7.3 Use and inspection of protective paintings

Whilst there are a lot of similarities to the repainting of a normal painted (organic coated) bridge, there are also significant differences:

- Blast cleaning the corroded surface will be essential. Due to the rough surface and the numerous pits in the corroded steel, it will be difficult to economically obtain as high a quality finish as would be possible with painted steel structures. Care must be taken in writing the specification to avoid specifying an unachievable standard.
- The paint system chosen must therefore be tolerant of large dry film thickness variations resulting from the rough surface of the steel substrate. This can be particularly important in choosing a primer, since a large quantity will be required to fill the profile, with great thickness variations. Experience has shown that up to four times as much primer is needed as for a smooth surface.
- The paint system should also be insensitive to residues of rust and chemical contaminants which are practically and economically impossible to remove entirely from the numerous pits.
- The paint system must have a low water vapour transmission rate to prevent osmotic blistering of the film.

Whilst trials may well be necessary to determine the best paint system for a particular application, experience has shown that a typical system which has performed well in the past consists of an epoxy zinc rich primer, with epoxy polyamide intermediate paints and urethane or vinyl top paints. This hybrid system of galvanic and barrier protection has been found to have excellent tolerance to variations in dry film thickness and good tolerance to surface contaminants and application errors. In generic terms, organic zinc rich systems perform better than inorganic.

On occasion, it is only necessary to apply a remedial painting to a limited area of a bridge. Typically, such areas are below expansion joints, where salt water leaks through. For instance, a specification may call only for painting the end metre of beams in such locations, although the implications on appearance would have to be considered. Other areas where limited remedial painting has been used are on the top of lower flanges, and perhaps a short distance up a web, where contamination (for example from salt-water spray from a highway below) may be worst.

Inspection of painted weathering steel is generally similar to that of normal painted structural steel, although the exact symptoms of failure may differ. The use of knowledgeable inspectors is essential, which can cause problems as previous experience is not great.
To extend the lifetime of the paint system, reduce local corrosion losses, and minimise life cycle costs, painting failures should be repaired, although the self-healing properties of the oxide layer may enable such repair to be postponed to a convenient time.

7.4 Enclosure

Modification of the local environment around steelwork, to preclude direct exposure and minimise airflow over the surface, has been shown to reduce the rate of, or even stop, corrosion of the steel. Such an environment is usually achieved inside box girders, but can also be achieved by enclosing plate girders within a “box” of maintenance-free sheeting material. Enclosure has been used in the United Kingdom to reduce the maintenance costs of new bridges in ordinary structural steel, and in one case has been used as an alternative to remedial painting of a bridge in weathering steel. However, it is considered unlikely that enclosures would prove economically viable as protection for weathering steel bridges in general.

8 GUIDELINES, RESEARCH AND REFERENCES

8.1 Guidelines

[1] Cerema, (2015). *Aciers autopatinables – Recommandations pour leur utilisation en structure des ponts et passerelles.* Sourdun: Cerema - Centre d'études d'expertise sur les risques, l'environnement, la mobilité et l'aménagement / IFSTTAR - now Université Gustave Eiffel.

[2] CIA, (2006). *Acier auto-patinable*. Brussels: Centre Inforamtion Aciers a.s.b.l (CIA).

[3] DASt, (1993). *DASt Richtlinie 007 - Lieferung, Verarbeitung und Anwendung wetterfester Baustähle.* Deutscher Ausschuss für Stahlbau - DASt e.V., Köln: Stahlbau-Verlagsgesellschaft mbH.

[4] EAE, (2011). *EAE - Instrucción de Acero Estructural*. Gobierno de España - Ministerio de Fomento.

[5] ECCS AC3 Bridge Committee, SCI, BCSA, (2001). *The Use of Weathering Steel in Bridges.* ECCS Publication No. 81, Brussels: European Convention for Constructional Steelwork ECCS CECM EKS.

[6] Fischer M, (2004). *Merkblatt 434 Wetterfester Baustahl.* Düsseldorf: Stahl-Informations-Zentrum.

[7] HERA, (2020). *HERA Report No. R4-97: New Zealand Weathering Steel Guide for Bridges.* (El Sarraf R, Mandeno W L, Karpenko M) Manukau: New Zealand Heavy Engineering Research Association (HERA).

[8] Highways England, (2019). *CD 361 - Weathering steel for highway structures.* Highways England.

[9] Mott MacDonald Praha, (2008). *Technické podínky TP 197 - Mosty a konstrukce pozemních komunikací z patinujících ocelí.* Praha: Ministerstvo Dopravy ČR.

[10] SCI, (2015). *SCI P185 GN 1.07 - Guidance notes on best practice in steel bridge construction - Guidance Note No. 1.07 - Use of weather resistant steel.* (6th issue), Berkshire: SCI (The Steel Construction Institute).

[11] SZS, (2005). *steeldoc 03/05 - Bauen in Stahl - Wetterfester Baustahl*. Zürich: SZS Stahlbau Zentrum Schweiz.

[12] Křivý V, Kreislová K, Rozlívka L, Knotková K, (2011). *Směrnice pro používání ocelí se zvýšenou odolností proti atmosférické korozi.* Praha: SVÚOM.

8.2 Research

[13] CISC, (May 2021). *Galvanized Bolts on Weathering Steel*. Canadian Institute of Steel Construction: https://www.cisc-icca.ca/galvanized-bolts-on-weathering-steel/.

[14] Díaz I, Cano H, Crespo D, Chico B, de la Fuente D, Morcillo M, (2018). *Atmospheric* corrosion *of ASTM A-242 ans ASTM A-588 weathering steels in differnt types of atmosphere*. Corrosion Engineering, Science and Technology (Vol. 53, No. 6), pp. 449-459.

[15] Fischer M, (2002). *Ist der heute im Stahlbau verwendete Baustahl optimal?* Stahlbau (Vol. 71, No. 6), pp. 13-21.

[16] Hoitomt M L, (2002). *Performance of Weathering Steel Tubular Structures*. Outdoor atmospheric corrosion, pp. 301-315.

[17] Kubzova M, Krivy V, Kreislova K, Hang H P, (2019). *Amount of Chlorides in Corrosion Products of Weathering Steel*. Transportation Research Procedia 40 (12th Internatonal Scientific Conference in Sustainable, Modern and Safe Transport (TRANSCOM 2019)), pp. 751-758.

[18] Kuhlmann U, Breunig S, Pascual A, Maier P, Zinke T, Ummenhofer H, Mensinger M, Pfaffinger M, Beck T, Lent K, Schneider S, Fischer M, (2019). *Holistic Assessment of Steel and Composite Railway Bridges according to Criteria of Sustainability (FOSTA P 978 / IGF No. 458 ZN).* Düsseldorf: Forschungsvereinigung Stahlanwendung e. V. (FOSTA).

[19] Kuhlmann U, Maier P, Zinke T, Ummenhofer T, Pfaffinger M, Mensinger M, Beck T, Lenz K, Schneider S, Fischer M, Friedrich H, Kascher R, Krieger J, (2016). *Holistic assessment of steel and composite bridges according to sustainability criteria (FOSTA P 843).* Düsseldorf: Forschungsvereinigung Stahlanwendung e. V. (FOSTA).

[20] Miazzon A, Maiorana E, (2003). *Rassegna del CTA, I (2003) No. 3*. Milano: Collegio des Tecnici dell'Acciaio.

[21] Slamova K, Glaser R, Schill C, Wiesmeier S, Köhl M, (29 June 2012). *Mapping atmospheric corrosion in coastal regions: methods and results.* Journal of Photonics for Energy (Vol. 2).

[22] Tibland J, (2013). *Atmospheric corrosion of heritage metallic artefacts: processes and prevention*. In P. Dillmann, D. Watkinson, E. Angelini, & A. Adriaens, Corrosion and conservation of cultural heritage metallic artefacts (pp. 37-52). Woodhead Publishing.

[23] Townsend H E, Gorman C D, Fischer R J, (1998). *Atmospheric corrosion performance of hot-dip galvanized bolts for fastening weathering steel guiderail*. Corrosion 98.

[24] UK Network Rail, (2016). *Weathering Steel Graffiti Removal Trails.* Manchester: Network Rail.

[25] Ungermann D, Hatke P, Walther F, Knyazeva M, Friedrich S, Lebelt P, (2021). *Innovations for the optimal use of weathering steel in steel and composite bridge construction (Final report of research project FOSTA P1200 / IGF 18655 BG).* Düsseldorf: FOSTA - Forschungsvereinigung Stahlanwendung e.V.

8.3 Availability

[26] ArcelorMittal Europe, (2016). *Indaten and Arcorox - Self-protecting steels with raw aesthetic.* Luxembourg: ArcelorMittal Europe Communications. https://constructalia.arcelormittal.com/files/Indaten_brochure_EN--edb22d98d8cf412a47dc520de4258099.pdf.

[27] Dillinger, *DIWETEN.* Dillingen: AG der Dillinger Hüttenwerke. https://www.dillinger.de/d/en/products/proprietary-steels/diweten/.

[28] SSAB, *SSAB Weathering - Optimized for you and low maintenance.* Stockholm: SSAB. https://www.ssab.com/brands-and-products/ssab-weathering.

8.4 Standards

[29] BS 7668, (2016). *Weldable structural steels. Hot finished structural hollow sections in weather resistant steels. Specification.* BSI British Standards Institution.

[30] EN 10025-2, (2019). *Hot rolled products of structural steels - Part 2: Technical delivery conditions for non-alloy structural steels.* Brussels: CEN European Committee for Standardization.

[31] EN 10025-3, (2019). *Hot rolled products of structural steels - Part 3: Technical delivery conditions for normalized/normalized rolled weldable fine grain structural steels.* Brussels: CEN European Committee for Standardization.

[32] EN 10025-4, (2019). *Hot rolled products of structural steels - Part 4: Technical delivery conditions for thermomechanical rolled weldable fine grain structural steels.* Brussels: CEN European Committee for Standardization.

[33] EN 10025-5, (2019). *Hot rolled products of structural steels - Part 5: Technical delivery conditions for structural steels with improved atmospheric corrosion resistance.* Brussels: CEN European Committee for Standardization.

[34] EN 1011-2, (2001). *Welding - Recommendations for welding of metallic materials - Part 2: Arc welding of ferritic steels.* Brussels: CEN European Committee for Standardization.

[35] EN 10365, (2017). *Hot rolled steel channels, I and H sections - Dimensions and masses.* Brussels: CEN European Committee for Standardization.

[36] EN 1090-2, (2018). *Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures.* Brussels: CEN European Committee for Standardization.

[37] EN 14399-1, (2015). *High-strength structural bolting assemblies for preloading - Part 1: General requirements.* Brussels: CEN European Committee for Standardization.

[38] EN 14399-10, (2018). *High-strength structural bolting assemblies for preloading - Part 10: System HRC - Bolt and nut assemblies with calibrated preload.* Brussels: CEN European Committee for Standardization.

[39] EN 1993-1-8, (2005). *Eurocode 3: Design of steel structures - Part 1-8: Design of joints.* Brussels: CEN European Committee for Standardization.

[40] EN 1993-1-9, (2005). *Eurocode 3: Design of steel structures - Part 1-9: Fatigue.* Brussels: CEN European Committee for Standardization.

[41] EN 1993-1-10, (2005). *Eurocode 3: Design of steel structures - Part 1-10: Material toughness and through-thickness properties.* Brussels: CEN European Committee for Standardization.

[42] EN ISO 12944-2, (2017). *Paints and varnishes - Corrosion protection of steel structures by protective paint systems - Part 2: Classification of environments (ISO 12944-2:2017).* Brussels: CEN European Committee for Standardization.

[43] EN ISO 8501-1, (2007). *Preparation of steel substrates before application of paints and related products - Visual assessment of surface cleanliness - Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings (ISO 8501-1:2007).* Brussels: CEN European Committee for Standardization.

[44] EN ISO 9223, (2012). *Corrosion of metals and alloys - Corrosivity of atmospheres - Classification, determination and estimation (ISO 9223:2012).* Brussels: CEN European Committee for Standardization.

[45] EN ISO 9224, (2012). *Corrosion of metals and alloys - Corrosivity of atmospheres - Guiding values for the corrosivity categories (ISO 9224:2012).* Brussels: CEN European Committee for Standardization.

[46] EN ISO 9225, (2012). *Corrosion of metals and alloys - Corrosivity of atmospheres - Measurement of environmental parameters affecting corrosivity of atmospheres (ISO 9225:2012).* Brussels: CEN European Committee for Standardization.

9 PICTURE CREDITS

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Weathering steel provides many economic and ecological benefits. The reason for this is an improved corrosion resistance due to the formation of a protective oxide layer without the need for an additional coating system. At the same time, weathering steel has similar material properties as non-alloyed structural steel. Therefore, the same rules and regulations for dimensioning, fabrication and installation apply without any significant additional effort. However, correct design and detailing, as well as suitable environmental conditions, are essential for the durable service of weathering steel.

This document is intended to serve as a guide for the use of weathering steel in bridge construction. For this purpose, in addition to extensive basic information on the use of weathering steel, many recommendations have been developed from the review of national and international guidelines and standards. Furthermore, latest research results are also included.

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The “Bridge Committee” (Advisory Committee 3 - AC3) has the objective to promote the use of steel in bridge construction. The AC3 Committee: i) deals with developing promotion tools for the development of the market for bridges in steel in Europe, ii) promotes and organizes the International Conference/Symposium on Steel Bridges since 1988, and iii) develops publications on steel and composite bridges (available in the E-Store).

The AC3 is part of the PMB and consists of bridge experts such as steel producers, fabricators, designers and academics. Next to its focus on promotion activities the committee is following the technical development in the steel and composite bridges domain.

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