Experience of duplex stainless steels as structural materials for bridges

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The use of duplex stainless steel (DSS) in bridge construction has increased significantly in the last twenty years because of the material’s high strength and good corrosion resistance. The high corrosion resistance of DSS results in a low maintenance requirement and hence low life cycle costs. There is now a range of DSS grades available and it is possible during the design phase to undertake a material selection exercise for DSS to align the required material performance with the bridge environment. Lean alloyed and less costly DSS grades can be specified in less harsh environments. This paper presents the results from inspection of various existing road, rail and pedestrian bridges. In each case a DSS was used for the main structure and each bridge illustrates the performance of the material in a representative European environment. The environments were retrospectively classified in accordance with the recently introduced EN 1993-1-4 Annex A and a comparison of actual performance made with the guidance given in this annex. Previous high-level cost studies have indicated that durable, low-maintenance bridge designs using DSS are achievable without incurring excessive initial construction costs, and that significant life cycle cost savings can be made over the life of the structure. The present work has confirmed that, when appropriately selected and used, DSS can be anticipated to give long service lives in bridge structures, greatly reducing corrosion problems that may necessitate re-painting and remediation of carbon steel structures.

1. Introduction

The structural use of duplex stainless steels (DSS) in bridge construction has increased significantly in the last twenty years. DSS are ideal for bridges because of their high strength, good corrosion resistance, very low need for maintenance and hence low life cycle costs. The use of stainless steel for structural applications is now recognized in design codes such as EN 1993-1-4 (Eurocode 3) and AISI Steel Design Guide 27[1,2]. Three DSS grades suitable for use in bridges are EN 1.4462 (UNS S32205), 1.4362 (UNS S32304) and 1.4162 (UNS S32101). All DSS have high strength, good fabrication characteristics and good weldability. In recent years the lean alloyed DSS 1.4162 has often been selected in preference to DSS 1.4462 and 1.4362 since it combines high strength with lower cost[1,4]. It is important to select the DSS grade that is appropriate for the intended service.
environment, bearing in mind that appropriate use of a leaner alloy can reduce costs. EN 1993-1-4 Annex A [1] sets out a methodology for selecting an appropriate grade of stainless steel for the service environment, using five Corrosion Resistance Classes (CRC I to V). The CRC are assessed in terms of three components: risk of exposure to chlorides from salt water or deicing salts (distance from the sea and roads), risk of exposure to sulfur dioxide and cleaning regime including natural washing by rain which has a cleaning effect. The standard suggests appropriate grades for the CRC classes. Different elements of the same structure may have different exposure conditions, i.e. one part may be fully exposed to rain and another part fully sheltered from it. However, there is little documented information available about the service performance of actual structures such as bridges made of DSS. The main objective of this paper is to present such information for seven DSS bridges.

2. Inspection procedure, results and comments for each bridge inspection

Seven different DSS bridges were inspected to assess durability in their actual service environment. The methodology used involved selecting bridge sites, visual inspection conducted at each site and later analysis in the laboratory. The criteria used for selecting the sites were: the type of DSS used for the main structure, the environmental conditions and the age of the bridge. The environment was classified in terms of the CRC class [1]. The selected bridges were between 4 and 12 years old at the time of inspection. All bridge structures are intended to have a service life and economic life longer than this. The age of the bridge structures inspected was considered to be adequate for making assessments of the suitability of the DSS selected for the service environments. The list of the DSS bridges inspected, including the DSS grade used, the type of DSS elements, the construction year, the CRC class and the estimated C-Class (Corrosivity class) [5] are given in Table 1. At each inspection site visual inspection was used to identify the condition of DSS elements and digital photographs used to record the condition of each element. Where access was possible, a hand-held X-ray spectroscopic analyzer was used to confirm the grade of steel used. Surface replicas were taken for surface roughness measurements in the laboratory. When any surface contamination was observed, the contamination was transferred to an adhesive scanning electron microscope (SEM) stub for subsequent analysis by SEM and Energy Dispersive X-ray Spectroscopy (EDS). For sites close to bodies of water, chloride ion (Cl\(^-\)) levels in the water were checked using a chloride test kit. A water sample was also taken for subsequent laboratory analysis of Cl\(^-\) content. In the laboratory surface roughness measurements were taken on the replicas using a confocal microscope. Any contamination was examined by SEM/EDS to identify the nature and chemical composition. The chloride ion level from water samples was analyzed by chromatography.

2.1 Road Bridge in Orrhammarvägen, Flen, Sweden – 1.4162, CRC II

The Orrhammarvägen Road Bridge in Flen, Sweden (Figure 1) is a composite bridge with concrete deck and abutment, supported by 1.4162 DSS beams and bearing plate. The environment was classified as CRC II with a low risk of exposure to Cl\(^-\) (>10 km from Baltic Sea) and SO\(_2\), and the DSS 1.4162 elements were in a sheltered condition. The inspection results showed that the performance of 1.4162 was very good with no sign of corrosion observed after six years exposure in service. Some accumulation of dirt was found on the underside DSS surfaces due to the sheltered position and lack of natural cleaning by rain. A superficial orange stain was noted at regular intervals along the bottom face of the bottom flange of one beam. A sample of the contamination was taken and analyzed by
Table 1. List of the DSS bridges inspected, the DSS grade used, the type of DSS elements, the year of construction, the CRC class¹ and the estimated Corrosivity C-Class³

| Steel Grade | Bridge name (Location)          | Year (Age¹) | DSS elements                      | CRC| Exposure² | Exposed condition | Estimated C-Class³ |
|-------------|--------------------------------|-------------|-----------------------------------|----|------------|-------------------|-------------------|
| 1.4162      | Orrhammarvägen Road Bridge (Flen, Sweden) | 2009 (6 y)  | Bridge beam, bearing plate        | II | L          | L                | Sheltered         | C2               |
| 1.4162      | Añorga Railways Bridge, (San Sebastián, Spain) | 2011 (4 y)  | Arch, beam                        | II/III | M          | L                | Open/sheltered    | C3               |
| 1.4162      | Road Bridge (Nynäsham, Sweden)     | 2011 (4 y)  | Bridge beam, Abutment plate       | IV | V          | L                | Sheltered         | C3               |
| 1.4362      | Puerto Arrupe Pedestrian Bridge (Bilbao, Spain) | 2003 (12 y) | Box girder                        | II/III | M          | L                | Open/sheltered    | C3               |
| 1.4362      | Celtic Gateway pedestrian Bridge (Holyhead, UK) | 2006 (9 y)  | Arch                              | III/IV | V          | L                | Open/sheltered    | C3               |
| 1.4462      | Pedestrian Bridge (Zumaia, Spain)  | 2008 (7 y)  | Bridge beam, balustrade           | III/IV | H          | L                | Open/sheltered    | C4               |
| 1.4462      | Cala Galdana Road Bridge (Menorca, Spain) | 2005 (10 y) | Arch, deck, balustrade            | IV/V | V          | L                | Open/sheltered    | C5               |

Notes: ¹ = Age of the bridge at the time of inspection  
² = Risk exposure to chloride Cl⁻ and sulfur dioxide SO₂: L = Low, M = Medium, H = High, V = Very high  
³ = Estimated corrosivity class in accordance with ISO 9223.

SEM-EDS. The result showed the stain was contamination by iron particles from carbon steel or a similar source. Due to the regularity of the spacing of contamination it was suspected that the beam had been resting on steel trestles at some point during its fabrication, transportation or installation. The contamination was superficial and had not affected the structural integrity of the beam.

Figure 1. Orrhammarvägen Bridge, Flen, and close up of underside periodic contamination
2.2 Añorga Railway Bridge in San Sebastian, Spain – 1.4162, CRC II/III

The main structural material of the railway bridge in Añorga, San Sebastian, Spain was DSS 1.4162. This bridge had replaced an existing carbon steel structure that had required intensive maintenance over its lifespan. The bridge is located about 3 km from the Bay of Biscay and has areas both with and without rain washing. The CRC was therefore II and III due to the moderate risk of exposure to chlorides.

![Añorga Railway Bridge](image)

Table 2: SEM-EDS result of the contamination on the DSS 1.4162 surface

|     | O | Mg | Al | Si | K | Ca | Fe |
|-----|---|----|----|----|---|----|----|
| AVG | 48.4 | 1.1 | 7.9 | 20.5 | 3.2 | 16.0 | 3.4 |

Figure 2. Añorga Railway Bridge (DSS 1.4162) in San Sebastian, Spain

The inspection results showed that the DSS 1.4162 was performing well, with no sign of corrosion. All stainless steel surfaces had a fine covering of dirt and dust. A sample of this showed that iron (Fe), aluminium (Al), calcium (Ca), magnesium (Mg) and silicon (Si) were present on the DSS surface, Table 2. These deposits were probably from the cement industry which is very near to the inspected site. This surface deposit was not causing any corrosion of the DSS.

2.3 Road Bridge in Nynäshamn, Sweden – 1.4162, CRC IV

The Nynäshamn bridge is a concrete composite bridge with DSS supporting beams, and is in a sheltered inlet off the Baltic Sea adjacent to an oil refinery. In accordance with the standard EN 1993-1-4 Annex A, which was published after the bridge was constructed, the environment condition is CRC IV, due to being a distance of less than 0.25 km from the coast and the absence of rain washing. The standard recommends that a high alloyed steel such as DSS 1.4462 material is required in this environment, but the bridge is constructed of DSS 1.4162, a lower alloyed grade. The results showed that the DSS 1.4162 performed well and appeared to be in good condition, as seen in Figure 3. Some cosmetic surface corrosion attack in the form of micro-pitting was observed on the beam. This is possibly due to the presence of traces of chloride found on the surface in combination with no washing by rain. However, these isolated micro-pits were superficial and not causing any deterioration to the structural performance. It is clearly seen that DSS 1.4162 is performing adequately in this location, despite being outside the recommendation given in EN1993-1-4 Annex A.

![General appearance of the composite bridge in Nynäshamn](image)

Figure 3. General appearance of the composite bridge in Nynäshamn, and isolated pits on the surfaces
2.4 Puerto Arrupe Pedestrian Bridge in Bilbao, Spain – 1.4362, CRC II/III

The DSS Bridge in Bilbao is located 10km from the Bay of Biscay, and acts as a link between the university and Guggenheim museum. The environment was classified as CRC II and III. The DSS grade 1.4362 was used for the support structure and external parts.

Figure 4. Puerto Arrupe bridge overall design, and close-up view of sides and sheltered underside

The inspection results indicated very good performance of DSS 1.4362 and no signs of corrosion were observed, see Figure 4. However, some discoloration of panels and spots of contamination were occasionally seen at the bridge box surface. Discoloration is likely due to limited washing by rain or from fabrication or transportation. The contamination spots were probably from fabrication processes - either grinding or spatter from welding. One panel was painted on the internal side surface at pedestrian level in order to cover graffiti. This is not normally a recommended method for dealing with such issues with DSS, and a more appropriate solution should be used.

2.5 Celtic Gateway Bridge, Holyhead, Pedestrian Bridge – 1.4362, CRC III/IV

The bridge in Holyhead (Figure 5) is adjacent to an ocean harbor, so it may be considered CRC IV due to salt exposure from the ocean. However, the harbor below the bridge is well sheltered, and therefore wave conditions are likely to remain calm. There is no high-speed water traffic passing under the bridge to generate splashing seawater. Consequently, the position of the ‘coast’ could be interpreted as being at the harbor mouth and that the bridge is therefore 800–900m from the coast in a CRC III environment. The Celtic Gateway Bridge spans over Victoria Road in Holyhead. The road is likely to be de-iced in winter by using grit/salt, and this would also result in a CRC III classification. In a CRC IV environment DSS 1.4462 is recommended by EN 1993-1-4. For CRC III the recommendation is DSS 1.4162 or 1.4362. This bridge is constructed of 1.4362, although it was found to have a particularly smooth surface finish (Ra=0.4-0.5 µm) which is known to be beneficial in improving corrosion resistance of stainless steels.

Figure 5. Celtic Gateway Bridge in Holyhead, UK; close ups of good condition, and localized run-off

The inspection result demonstrated that the arch surfaces and detailing made of DSS 1.4362, were in generally good condition as shown in Figure 5. Some lime was deposited and appeared to be from water run-off from the concrete deck onto DSS surfaces. This was not causing any damage to the DSS.
2.6 Pedestrian bridge in Zumaia, Spain – 1.4462, CRC III/IV

The first pedestrian bridge constructed of a combination of DSS and glass fiber reinforced plastic is in Zumaia, Spain over the Narrondo River (Figure 6). The marine climate with high risk of exposure to chloride (about 1km from Bay of Biscay) required a highly corrosion resistant grade such as 1.4462.

![Figure 6. Pedestrian Bridge (DSS 1.4462) in Zumaia, Spain, with DSS elements performing well. One incidence of a balustrade endplate with orange-brown deposit of carbon steel contamination](image)

The inspection result show that DSS 1.4462 was performing very well in this highly corrosive environment without any sign of corrosion to the DSS itself. The only exception was that some grey staining and discoloration was observed on the surface. The main cause of the damage found on this bridge was contamination. One specific area of balustrade top surface and end plate showed an orange-brown stain, as seen in Figure 6. It was speculated that this orange stain could be from the fabrication (grinding or cutting) of a carbon steel fence that is adjacent to the bridge. It is usually possible to remove this type of contamination by use of dilute acid-based cleaners, and restore the appearance of the DSS to be similar to the majority of the bridge.

2.7 Road Bridge in Cala Galdana, Menorca, Spain – 1.4462, CRC IV and V

This bridge in Menorca was the first stainless steel road bridge in Europe. The DSS bridge replaced an existing concrete bridge that was only 30 years old but exhibited significant degradation due to the very corrosive marine environment. The environment condition for this bridge was classified as CRC IV and V due to very high risk to chloride (<0.25 km from the sea) and elements exposed with and without rain washing. A suitable grade for this class is DSS 1.4462. The site X-ray spectroscopy found that this bridge uses two stainless steel grades for the major components. DSS 1.4462 is used for the bridge arches and balustrades (Figure 7).

![Figure 7. Cala Galdana Bridge (DSS 1.4462) in Menorca, Spain, with close up of arch and underside](image)

The austenitic stainless steel grade 1.4401 (ASTM 316), which has a lower corrosion resistance than 1.4462, is used for a tubular barrier between vehicle and pedestrian areas of the deck. Both alloys are
finished with a similar surface roughness (Ra 3.5-4.0µm), however the performance is noticeably different. The 1.4401 is covered with orange-brown staining, resulting from a corrosion reaction with the coastal atmosphere, whereas the DSS 1.4462 has a good appearance. The beams (DSS 1.4462) located under the bridge deck were also in a good condition, despite being used in a position with no rain washing. Some white staining appeared to be deposits of carbonate washing out of the concrete bridge deck. This has not adversely affected the stainless steel.

3. Guidance on use of DSS as a construction material in bridges for specific environments

Seven DSS bridges have been inspected in environments which were classified in accordance with EN 1993-1-4 Annex A. The inspection results show that correct selection of a stainless steel grade for the actual service environment is the most significant factor affecting the long term durability of the bridge structure. The surface condition is also of importance, as illustrated by the DSS 1.4362 Celtic Gateway Bridge in Holyhead, UK where the good performance may be partially attributed to the smooth surface finish as well as grade selection.

Table 3. Summary of the inspection results

| Bridge name                  | Designation EN (UNS) | DSS elements          | Surface roughness Ra µm | Cl- Level in water ppm | Cause of damage | Loss of structural integrity |
|------------------------------|----------------------|-----------------------|-------------------------|------------------------|-----------------|-----------------------------|
| Orrhammarvägen Road Bridge   | 1.4162 (S32101)      | Bridge beam, bearing plate | 4.0-6.0                | ~10                    | Contamination, transportation | 0*                     |
| Añorga Railways Bridge       | 1.4162 (S32101)      | Arch, beam            | ~8.0                    | Not tested             | Contamination   | 0                          |
| Road Bridge                  | 1.4162 (S32101)      | Bridge beam, Abutment plate | 6.0-8.0                | ~20                    | Micro-pitting   | 1                         |
| Puerto Arrupe pedestrian Bridge | 1.4362 (S32304)     | Box girder            | 3.0-5.0                | ~2500                  | Contamination   | 0*                       |
| Celtic Gateway pedestrian Bridge | 1.4362 (S32304)     | Load bearing arch     | 0.4-0.5                | Not tested             | n/a             | 0                         |
| Road Bridge                  | 1.4462 (S32205)      | Bridge beam, balustrade | 4.0-6.0                | ~15000                 | Fabrication     | 0*                       |
| Cala Galdana Road Bridge     | 1.4462 (S32205)      | Arch, deck, balustrade | 3.5-4.0                | ~17000                 | n/a             | 0                         |

Note: Loss of structure integrity: 0 = no corrosion, 1 = cosmetic surface micro-pitting, 2 = corrosion that might require repair for reasons of structural integrity, 3 = general attack by the environment with loss of structural integrity.

* Cosmetic staining observed that was attributed to contamination with mild steel

Minor problems found during inspection were generated by contamination during fabrication, installation or transportation. The results obtained in this work can be used as examples of successful application of DSS structures. They can also be used to provide data for future revisions of EN 1993-1-4 Annex A, relating to materials selection. For example, the bridge in Nynäshamn, Sweden and the Celtic Gateway, Holyhead, UK, indicate that the CRC may be too conservative in some cases. An overall summary of results is given in Table 3. A study of construction costs using a reference composite road bridge design has been previously undertaken[6]. This high-level cost study demonstrated that similar build costs in DSS 1.4162 compared to using S355 carbon steel bridge
beams could be achieved if the design of the DSS beams was optimized to utilize the higher strength ($R_{p0.2} = 460\text{MPa}$) of DSS. A further study[7] examining the impact on life cycle costs concluded that direct savings of up to EUR 140K (discounted to present day value and not including costs for disruption and loss of amenity during maintenance) could be anticipated over a 60-year life through the reduction in repair and re-painting costs. The hypothesis in this earlier work was that little maintenance of DSS would be required, and this assumption has been shown to be valid by the inspection work presented in this paper. DSS has been used in bridge structures built in the last 20 years, hence it is not possible to check older structures to confirm the very long term performance, although it is noted that design lives are often up to 120 years. Nevertheless, it is generally known that the corrosion performance of stainless steels in the built environment is stable over the long term, and that if significant corrosion problems will occur, the onset of such problems will most likely be easily identifiable within the first 6 – 36 months of service.

4. Conclusion

DSS offers a long-term cost effective option for bridge construction with minimal requirement for maintenance throughout the life of the structure. In this investigation, the performance of DSS for existing bridges under specific service environments was good. Occasional minor problems were cosmetic, with surface discoloration generally caused by contamination from carbon steel during fabrication, transportation or in-service. These had not resulted in loss of structural integrity, and can be eliminated. The results obtained from this exercise can be used as illustrative examples of successful application of DSS bridge structures and used to provide data for future design standard revisions of EN 1993-1-4 Annex A relating to materials selection. The present study examining the performance of bridges in service has confirmed that a high corrosion resistance can be expected of DSS, when appropriately selected for the particular environmental conditions. The hypothesis that a low level of maintenance is required for duplex stainless steel bridge elements has been validated. It would be valuable to carry out repeat inspections of these structures after a further 10 – 20 years of service to confirm the ongoing performance.

5. References

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