Stainless Steel in Civil Engineering Applications

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Introduction

The use of stainless steel in civil engineering applications is not a new idea, the use of what we now know as austenitic stainless steel can be traced back to at least the 1930's where the reinforcement of the Progresso Pier in the Gulf of Mexico used an equivalent to a modern grade 1.4301 steel. Perhaps one of the best-known examples of the use of stainless steel for a civil engineering application in the UK is for the roof domes of the Thames barrier. In both the above cases the materials were chosen primarily for the resistance to corrosion that they could provide in what was considered to be a harsh service environment.

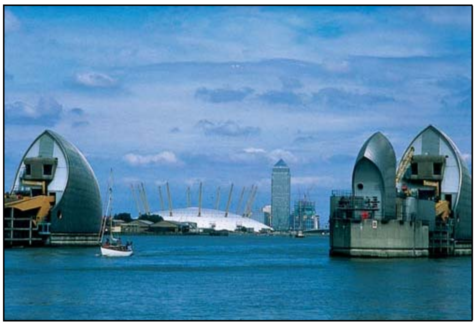
Figure 1Thames Barrier

There are many other examples of the use of stainless steels in the construction industry, on both a small and large scale. However, most of the common examples of the use of stainless steel as a primary structural engineering material have been in buildings or as critical components in structures as opposed to the widespread use as structural engineering materials in their own right.

However, an increasing awareness, desire and changing political climate has led to a situation where currently many designers and client bodies are more open to the use of stainless steel. The drivers for this apparent change in attitude do not appear to be clearly defined but include:

- An increased awareness of the future burden of using materials that are not inherently durable in the service environment.
- An increase in desire to reduce or eliminate the need for maintenance (both planned and unplanned) that can arise with accepted structural materials.
- In some applications it is now perceived as politically undesirable to produce structures that are not inherently durable.

These factors do not necessarily provide an "open door" for the use of stainless steel as a structural material as there will be competition from other materials however, this change in attitude does provide a climate in which stainless steels may be considered more favourably than in the past.

This paper considers the problem of durability with conventional construction materials in relation to bridges but could be applied equally to other civil engineering structures and the possible scope for increasing replacement of these materials with various types of stainless steel.

Durability of conventional structural materials

The two main structural engineering materials that are now used for civil engineering applications are reinforced concrete (using carbon steel reinforcement) and structural steel. These materials have been shown to be very flexible in the construction industry and have proven, or at least known, performance in a wide range of service environments. However, in some conditions neither material are regarded as inherently durable and it is common, in these instances, to modify or provide additional protection to improve the durability and achieve the design life. This is particularly so for civil engineering structures where long (>100 year) is often a basic design requirement.

Reinforced Concrete

In the case of reinforced concrete the realisation that the material may not always be durable in some conditions has occurred over the last 25 years or so as the impact of chlorides (from whatever source) on the long-term performance of structures has become apparent. The problems can be particularly acute on highway structures, such as bridges, and has led to the development of a range of repair strategies to avoid demolition and reconstruction of these structures. The problems of corrosion arising from the use of road de-icing salts can often occur within a relatively small fraction of the intended design life (15 to 20 years out of an intended 120 years). The resultant maintenance, repairs and monitoring of such structures is:

- Difficult
- Expensive
- Increasing unacceptable

Figure 2 Example of concrete repairs to North Seaton Bridge

In response to these difficulties national design codes and specifications now go to considerable lengths to ensure that modern designs take the issue of durability seriously and many prescribe rules that should be followed to ensure a durable structure. These national documents are often supplemented by specific requirements of client bodies, such as the UK Highways Agency. For the most part the approach is to attempt to improve the resistance of the concrete to detrimental affects of chlorides by restricting the transport of chlorides through the concrete to the steel reinforcement. In broad terms this is achieved by one or more of the following:

- Increasing the thickness of cover to the reinforcement, thereby increasing the time for chloride transport to the steel.
- Altering the specification of the mix to include cement alternatives that result in a concrete that is less permeable to chlorides; thereby increasing the time for chloride transport to the steel.
- Improving the overall quality of the concrete to ensure a low permeability to chlorides.
- Treatment of the surface (using coatings or impregnation materials) to prevent the ingress of water and chlorides into the concrete; such methods require future maintenance.

It can be seen that in some way all of the above an attempt:

- To modify the service environment that may occur around steel reinforcement for the assumed design life.
- In some degree this modification is based on assumptions in changes to the environment over time.
- In some all are dependent on site workmanship and thus subject to unpredictable variation.

No doubt these methods are successful in improving durability but they increase the complications of construction and are essentially dealing with something, the service environment that is unpredictable. It is somewhat surprising that, given the unpredictability and complexity of the environment, it is only recently that the use of materials that are inherently resistant to corrosion in the worst possible conditions have received serious consideration as an alternative approach to the issue of corrosion of reinforcement in concrete. The advantages of using corrosion resistant materials, such as stainless steels, are that they would:

- Provide a solution to reinforcement corrosion that uses materials that are inherently corrosion resistant in the service environment.
- Eliminate the risk of in service failure and unplanned maintenance within the design life of the structure.
- Greatly reduce the need for maintenance of to the main structural components of structures.

Probably the biggest single reason why alternative reinforcement materials have not been used is the perception that such materials would have a significant impact on the construction costs. It is also probably true that the manufacturers of alternative reinforcement have been somewhat slow to see the opportunities and allowed others to set the agenda in terms improving durability.

As far as UK highways structures are concerned the HA have recognised the importance of designing for durability to reduce the future maintenance costs associated with the UK motorway and trunk road network. They have developed their own standards and advice documents on preferred methods of achieving required durability. The current edition of the relevant standard for durability, BD57[1], places onus on the designer to consider a range of options to improve the durability of highway structures. One of the options that are given is the use of corrosion resistant reinforcement, including stainless steel. Further to the publication of the standard the HA also published an advice note, BA84/02[2], that provided guidance on the use of stainless steel reinforcement.


Figure 3 Broadmeadow Bridge

The approach adopted by the advice note is one that encourages the appropriate use of stainless steel and limits its use to those structures, or parts of structures, where the risk of chloride induced corrosion is greatest. It is also implicit in the advice note that stainless steel might also be considered for structures where the risk of premature deterioration of the structure would be unacceptable for a number of reasons, such as:

- The difficulty of access for maintenance would make this prohibitively expensive.
- The disruption to the road network resulting from maintenance works would be unacceptable.

The BA also recommends that where stainless steel reinforcement is used some of the other rules within standards, relating to the design for durability with respect to carbon steel reinforcement, maybe relaxed. Such rules include reducing the concrete cover, omission of surface treatments and increasing the allowable crack width in concrete (this can have a beneficial affect in reducing the overall reinforcement requirements).

In addition to the HA publications it should also be noted that the UK has the only national standard for stainless steel reinforcement, BS6744:2001[3], in Europe. This standard now covers a wide range of materials and products made to the standard will be at least equivalent in terms of mechanical properties to carbon steel reinforcement. The publication of BD57 and BA84 are somewhat unique in terms of their requirements and in the case of the latter the guidance that they provide. BA84 is also based on the latest version of BS6744 in terms of recommendations on strength grade, material type (grade) and preferred bar sizes. It would therefore appear that all the component parts are in place to encourage the use of stainless steel reinforcement.

It is almost a year since the publication of BA84 and the document remains largely unknown outside those with a particular interest in stainless steel or an intimate knowledge of the detail of the Design Manual for Roads and Bridges[4]. This is unfortunate. Unless the stainless steel bar is more actively promoted, in conjunction with the documents referred to, in the near future then it is possible that the opportunity presented by publication will be missed.

The standards referred to above do not provide a serious or significant estimate of the cost implications of using stainless steel reinforcement as a replacement for carbon steel. Subsequent to the work that led to the publication of BS6744 and BA84 additional work was commissioned to explore the possible costs associated with using stainless steel reinforcement. The initial work in this area was sponsored by AvestaPolarit and more recently by the BSSA. The work examined two typical bridge structures, originally designed with carbon steel reinforcement, and used BA84 rules and redesigned both structures with stainless steel reinforcement. The broad results in terms of initial construction cost increases are estimated as being between 2% and 15% depending on the severity of exposure. In addition the BSSA have also developed a cost tool that uses the reinforcement quantities for the various design cases and allows the cost of reinforcement replacement to be calculated using actual market prices for stainless steel reinforcement. It is understood that BSSA will be publishing this model and the associated reports in the near future.

Although stainless steel now appears to be in a strong position to develop as a reinforcement material for use in concrete it is by no means the only option covered in BD57. There are any number of competitors including the use of chemical inhibitors, alternative concrete designs and also the use of fibre composite reinforcement. Of the options given in the BD stainless steel remains the only one that can claim to be both an inherently durable design solution and one that requires no change of existing analytical design tools.

Structural Steel

Structural steel has proven to be an almost infinitely versatile material for use in construction. Modern design tools and fabrication methods have made the material very competitive for many applications. However, the Achilles heel of structural steels remains durability. Structural steel will corrode in just about all naturally occurring environments and the issue for designers is not:

"Will it corrode within the design life?" but
"How fast will it corrode and/or how much section will be lost within the design life?"

It therefore follows that structural steel design accepts the inevitability of corrosion and that some means of preventing this must be put in place during construction.

Figure 4 Oresund Crossing

For land based civil engineering projects the most common method of providing protection is the application of a protective coating during construction. Over the years the specifications for such coatings has been developed such that modern specifications can be used with a high degree of confidence, with respect to the anticipated performance of the coating specification. However, even with modern coatings specifications it is impossible to achieve the required design life using a protective coating without very significant maintenance several times within the design life. For example Highways Agency standard specifications assume the maximum period to first maintenance of 25 years and even the most optimistic assessment of other, more modern specifications, would not extend this much beyond 30 or 35 years.

Alternative approaches to durability have been explored and used in bridge construction, most notably through the use of so called weathering steels. These are carbon steels with minor alloying additions of copper that form a stable patina on the surface of the steel and thereafter corrode much more slowly than conventional structural steels. Again these materials do work and need not require maintenance within the design life; provided the material is treated correctly and used in an appropriate environment (essentially one that is free of excess pollutants, chlorides and is regularly wetted by rain and dried. These environmental constraints do somewhat limit the use of the material as does the appearance of the steel which to the layman appears to be simply rusty steel.

As with the case of concrete reinforced with carbon steel, structural steel (even in the coated form) represents a material that is not inherently durable in most service environments. However, in the case of structural steel the methods and materials used to enhance durability are perhaps better understood and the consequences for maintenance are more readily predicted. None the less there are applications where the difficulty and cost of maintaining steel structures will warrant consideration of materials, such as stainless steels, that are inherently resistant to corrosion in the service environment.

The impediment to the use of stainless steels in lieu of structural steels is not simply the material cost itself but this combination with the weight of steel that is required for a typical structure such as a motorway bridge. In most cases this combination of factors will tend to make the use of stainless steel unattractive, unless significant weight savings can be achieved. This is unlikely to be the case with standard austenitic steels that do not have comparable strength to the steels commonly used in bridge construction. The obvious solution to this would be to use duplex stainless steels, which have increased yield strength. However, in many instances the design of longer span structures will be controlled, at least in part, by considerations of deflections as much as strength per se. Given the elastic modulus of duplex steel is very similar to that of carbon steel there may be little benefit in using this material.

None the less there are applications where stainless steel is used as a replacement for carbon steel and there is scope to increase the use of stainless steel in the future. The areas of use of stainless steel can be, broadly, considered as being:

- Structures where the difficulty and/or costs of maintenance make other alternative materials prohibitively expensive when considered using life cycle cost analysis.
- Components of structures that are critical to integrity or function of the structure where the owner does not want an inspection/maintenance/ replacement burden for the future.
- On structures or parts of structures where the mechanical properties of stainless steel can be used to advantage in conjunction with corrosion resistance.
- On structures that are required to have a particular, or high, aesethic appearance.

In practice of course it is more likely that that a decision to use stainless steel would be made on a combination of more, or indeed, all of these factors.

It is perhaps unsurprising that the examples of use of stainless steel on bridges has tended to be on those structures where there has been a requirement for structures with particular visual characteristics. Examples such as the Spencer Street Bridge, Melbourne that used austenitic stainless steel or the Millennium Footbridge, York that used duplex steel. These were high profile projects that in some way or other made a statement, traditionally stainless steels have been strong in such markets. However, in both these examples the stainless steel was not used simply for appearance it was used as primary structure.

In the case of Spencer Street the original design was for all the main structural elements to be fabricated from stainless steel, including the main trusses. Although this truss was subsequently changed to carbon steel to save money the remaining stainless steel components that are more visible to the public, but also fulfil a structural function remain stainless steel. In the case of the York footbridge it should be clear that the main arch, fabricated from duplex steel, is not only an architectural feature but also a primary structural element.

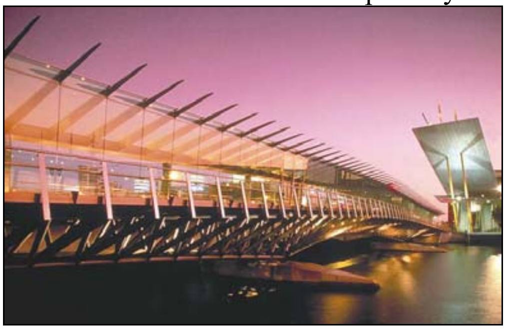

Figure 5 Spencer Street Footbridge, Melbourne

A much larger scale use of stainless steel is planned for the Stonecutters Bridge in Hong Kong. This is a cable-stayed structure with a main span of over 1km that is subject to very significant wind loads. The main span is supported from two towers each of which is 300m high. The structural design of these towers requires the top third of each to be constructed as a composite section; with an inner core of reinforced concrete connected to an external skin of steel. This section of the tower is approximately 30m in circumference and conical in shape. The original design used carbon steel plate for the skin and was to be painted. However, as part of the durability review during design it became clear that any coating applied to the steel would require significant maintenance during the design life of the structure. For a tower such as this access for maintenance would be difficult, expensive and require special provisions for access to the surface of the tower.

The durability led the design team to explore the possible use of stainless steel as the structural material for the skin. Initially, discussions centred on the type of austenitic steel and quality of finish appropriate for use in an essentially polluted marine environment. To some extent these discussions were overtaken, it became clear that the structural needs of the material required a material with yield strength of at least 400N/mm² at a plate thickness of 20 to 25mm; this naturally leads to the selection of duplex type steel.

The possible use of duplex steel for the skin is now being explored further with the fabrication of a representative full-scale prototype by Ancon in the UK. This prototype will explore the feasibility of fabricating the design and also the practicality of achieving an acceptable level of finish.

Conclusions

In the UK and Europe the case for using stainless steel as an alternative reinforcement material has been well made and the relevant guidance for designers is in place. Whether there is an increase in the use of stainless steel reinforcement is now dependent on increasing the awareness of designers and owners of structures that might benefit from using this type of reinforcement. This is now really a task that should be undertaken by those with an interest in promoting the use of the material.

The use of stainless steel plate and sections on bridges, as a primary structural material, is an area of increasing interest and this may lead to a more widespread use on structures such as bridges. If the use is to increase to the stage where it is no longer uncommon or restricted to high profile structures a number of questions need to be more thoroughly researched. Clearly, there will some initial cost penalty in using stainless steel and more work is needed to identify the significance of this and ways to reduce the premium associated with these materials. This penalty is likely to be most severe for standard austenitic materials that do not have comparable strength to the grades of carbon steel that are currently used; this reduction in strength may lead to an increase in the volume of material that is required to achieve the same result.

There may be more scope for the use of duplex steels in situation where the improved strength can be used to advantage. But for many structures strength per se may not be the determining factor in the design, this would be the case where the design is strongly influenced by deflection criteria. As the elastic modulus of duplex and carbon steels is similar there may be little structural advantage in changing materials. However, it may be possible to derive alternative design solutions to meet the deflection criteria when using duplex steels.

It should also be remembered that the types of structures described in this paper, and indeed typical highway bridges, represent only part of the bridge population. There are many other shorter span structures where deflection criteria do not dominate design considerations and in these instances there is opportunity for investigating the use of stainless steels as an alternative, maintenance free structural material.

References

1) BD57/01 "Design for durability", Design Manual for Road and Bridges, Volume 1 Section 3 Highways Agency 2001.
2) BA84/02 "Use of stainless steel reinforcement in highway structures", Design Manual for Road and Bridges, Volume 1 Section 3 Highways Agency 2002.
3) Design Manual for Roads and Bridges, Highways Agency 2002.
4) BS6744:2001 "Stainless steel bars for the reinforcement of and use in concrete – requirements and test methods", BSI, 2001.