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Structural uses of stainless steel — buildings and civil engineering

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A B S T R A C T

Stainless steels have not traditionally been widely used as structural materials in building and civil engineering. Where the steels have been used for this purpose there has been some other imperative driving the design, usually corrosion resistance or architectural requirements rather than the inherent structural properties of the steel. The primary reason for this low use in structural applications is usually the perceived and actual cost of stainless steel as a material. Developments over the last 10 years, both in available materials and attitudes to durability, are now offering a new opportunity for stainless steels to be considered as primary structural materials.

1. Introduction

This paper introduces stainless steel alloys and briefly discusses the important properties and commercial aspects of these alloys relevant to structural designers. The paper also considers recent developments, particularly with respect to available alloys and considers obstacles to the wider use of stainless steels in structural engineering that are related to both supply chain costs and efficiency of design.

The paper relates to the use of hot rolled and fabricated products. It should be remembered that cold rolled/formed stainless steels that take advantage of the work hardening capacity of stainless steels can also be used for structural applications as can ribbed reinforcement bars for concrete.

2. Stainless steels

Stainless steel can be a confusing material to those unfamiliar with the alloys as the term stainless steels refers to a large family of material types and alloys. For structural engineering there are two families of alloys of interest: the austenitic and duplex stainless steels. All these steels are alloys of iron, chromium, nickel and to varying degrees molybdenum. The characteristic corrosion resistance of stainless steels is dependent on the chromium content and is enhanced by additions of molybdenum and nitrogen. Nickel is added, primarily, to ensure the correct microstructure and mechanical properties of the steel. Other alloying elements may be added to improve particular aspects of the stainless steel such as high temperature properties, enhanced strength or to facilitate particular processing routes.

Table 1
Austenitic stainless steels major alloy element compositions

Steel designation (EN10088)	Alloy composition (Min%) from EN10088		
	Chromium	Nickel	Molybdenum
1.4301	17	8	–
1.4404	16.5	10	2
1.4435	17	12.5	2.5

2.1. Austenitic stainless steels

These are the steels most architects, engineers and lay people think of as stainless steels and some examples are given in Table 1 using the EN designation and compositions as given in EN 10088 Part 1 [1]. The term austenitic refers to the microstructure of the steel.

2.2. Duplex stainless steels

These steels are less familiar to most architects and engineers and have not been widely used in structural engineering. Examples using the EN designation and compositions from EN10088 Part 1 [1] are given in Table 2. Duplex steels have a mixed austenite/ferrite microstructure, hence the name.

Recent developments in alloy technology relevant, to structural engineering, have seen the introduction of newer low alloy duplex steels, often referred to as lean duplex steels. Examples from Table 2 are 1.4162, and 1.4362. These steels are characterised by comparable strength to established duplex grades but lesser resistance to localised corrosion although comparable to established austenitic steels.

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Table 2
Duplex stainless steels major alloy element compositions — note steel 1.4162 is not included in the current edition of EN10088 but is proposed for inclusion in the next revision

Steel designation (EN10088)	Alloy composition (Min%) from EN10088			
	Chromium	Nickel	Molybdenum	Nitrogen
1.4462	21	4.5	2.5	0.22
1.4410	24	6	3	0.35
1.4362	22	3.5	0.1	0.05
1.4162 (LDX2101)	21.5	1.5	0.3	0.22

Table 3
Mechanical Properties of austenitic and duplex stainless steels from EN10088 Part 2 and 3 — note steel 1.4162 is not included in the current edition of EN10088 but is proposed for inclusion in the next revision

Steel designation	0.2% Proof stress/N mm^{-2}	Ultimate tensile stress/N mm^{-2}	% Elongation	Elastic modulus/kN/mm^2
1.4301	210	540	45	200
1.4404	220	530	40	200
1.4435	220	550	40	200
1.4462	460	700	25	200
1.4362	400	650	20	200
1.4162 (LDX2101)	450	660	25	200

3. Mechanical properties of stainless steels

Typical mechanical properties for both austenitic and duplex stainless steels are given in Table 3. The values are from EN10088 Parts 2 and 3 [2] for hot rolled steels in the annealed condition. It can be seen that austenitic steels have relatively low strengths compared to both the duplex stainless steels and carbon steels typically used in structural engineering with yield strength of 350 N/mm^2.

The stress–strain behaviour of duplex and austenitic steels in a tensile test differs from that of hot rolled carbon steels in that the stainless steels show no clearly defined yield point. It is thus usual to define the yield point in terms of a 0.2% proof stress and it is the minimum value of proof stress that is typically used as the design strength for stainless steels.

Stainless steels are also characterised by:

- A high degree of plasticity between the proof stress and the ultimate tensile stress.
- Very good low temperature toughness.
- A degree of anisotropy.

These characteristics and their influence on structural design are discussed in design guidance documents such as those published by the SCI [3].

4. Stainless steel costs

The mill price of stainless steels is comprised of two parts:

- The base production cost that is set by the steel maker.
- The Alloy Adjustment Factor (AAF) that relates to the current price of alloy elements. The AAF is not directly controlled by the steelmaker.

The AAF tends to dominate mill costs of stainless steel and is significantly influenced by the price of nickel on the London Metal Exchange. The AAF is also influenced by molybdenum costs although this cost has less dominant than the nickel price. The AAF can be very volatile reflecting activity on the LME, thus it not only influences the absolute price of stainless steel but also causes price instability. Each steel producer publishes the AAF monthly for various steel grades and it is usually available via the producer's website. Variations in AAF are shown in Fig. 1 for 2007.

The effect of nickel prices on both the cost and stability of stainless steels prices is the most significant factor in holding back the use of stainless steels. It can be seen from Tables 1 and 2 that austenitic steels would be expected to be most influenced by variations in nickel price due to the high content of this alloying element in these steels. In comparison duplex steels have lower nickel content and are less affected by prices and the AAF; broadly this is found to be the case.

The actual cost of stainless steel fabrication is clearly not related solely to the ex mill price of base material, the final cost will be dependent on other factors and parts of the supply chain. These include:

- The procurement route — mill, mill service centre, stockist or trader.
- The supply condition — base plate, cut and prepared plate, specified surface finish quality etc.
- The cost of fabrication — fabrication costs are likely to be somewhat higher than carbon steel due to higher consumable costs and lower production rates.
- The requirement for a finish — architectural finishes add significant cost.
- The workmanship standard specified for the work.

For stainless steels these various factors are less well understood than for carbon steels and obtaining real data is difficult. However, experience on our own projects suggests that actual costs for stainless steel fabrications are disproportionately more expensive than the same fabrication in carbon steel. The reasons for this disparity cannot be easily explained on the basis of material cost and/or increased fabrication costs alone and it is an area that is in need of more detailed research.

5. Corrosion resistance of stainless steels

It is beyond the scope of this paper to consider this in great detail; it is a complex subject that is dealt with in detail by standard texts and in the literature. However, some appreciation of corrosion resistance is important if appropriate alloys are to be chosen for a given application.

There are two broad categories of corrosion that need to be considered:

- General or uniform corrosion which refers to a general corrosion and loss of section over the entire surface of the metal. All austenitic and duplex stainless steels are resistant to this type of corrosion in atmospheric conditions and water (sea or fresh) immersion.
- Localised corrosion which refers to surface staining, pitting, crevice corrosion and stress corrosion cracking (SCC). Stainless steels have varying resistance to these forms of corrosion and in broad terms the resistance can be related to the alloy content for a given environment.

One method of ranking corrosion resistance is to use the Pitting Resistance Equivalent (PRE) which can be calculated from the alloy content:

$$\text{PRE} = \text{Cr}\% + 3.3\%\text{Mo} + 16\%\text{N}.$$

Care is needed in using this formula and it should not form the sole basis for the selection of stainless steels or for assessing corrosion resistance in an absolute way. This is particularly so in relation to crevice effects and use of stainless steels immersed in seawater. Nonetheless, the formula shows the broad effect of alloy composition on corrosion resistance of the various austenitic and duplex grades.

The selection of a particular grade of steel, based solely on corrosion resistance, is related to corrosion risk in a particular

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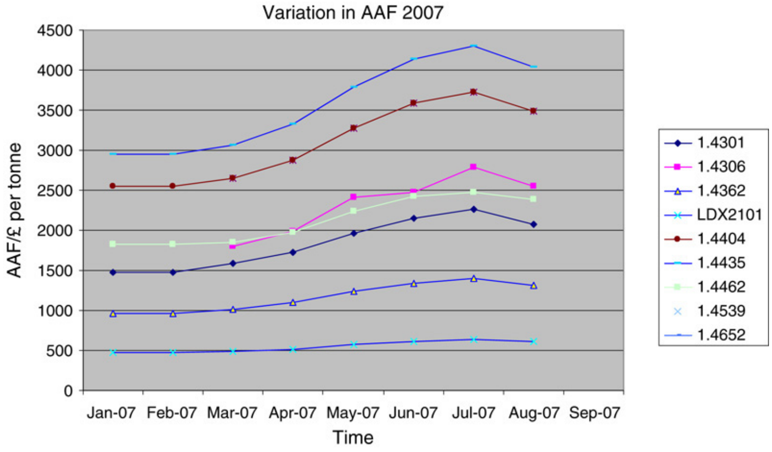

Fig. 1. Variation in AAF for various alloys.

location and the significance of that risk. This in turn will be related, to a greater degree than anything else, on the exposure to chlorides that might be encountered in the service environment. It is difficult to provide definitive advice on this but information is available from steel producers, national Stainless Steel Development Associations, independent experts and increasingly online; for example in the built environment the IMOA architects guide [6].

Generally experience and guidance has developed for the austenitic steels and higher alloy duplex steels and materials selection considers the interaction of several environmental and physical factors to select an appropriate material. These factors would include:

- The macro environment at a particular location.
- Exposure to chlorides from natural or man made sources.
- The impact of micro environments on the structure or component that may influence long term performance. For example the presence of crevices or sheltering of components from natural rain washing.
- The quality of surface finish (in terms of surface roughness).
- The impact that fabrication may have on corrosion resistance at joints.

Within these broad categories there are subtleties and nuances that may, in particular applications, influence the selection.

There is a degree of familiarity with selection of austenitic steels that is absent with respect to the duplex steels, particularly the newer generation lean alloys and how these new steels might be used in relation to the austenitic counterparts. This issue is being addressed both by producers and users of duplex stainless steels through laboratory test data, exposure trials and use on real structures. This has led to a comparable ranking of the austenitic and duplex steels as show graphically in Fig. 2 which is based on Arup experience on materials selection for bridges [4] and buildings and published data [5]; the boundaries between resistance, particularly of the leaner duplex steels, remains an area of some uncertainty. The ranking in Table 2 is applicable to structures for use on land or in coastal locations where immersion in seawater does not occur. Where seawater immersion is likely, crevice corrosion risks are more pronounced and specialist advice should be sought with respect to materials selection.

Fig. 2 shows that duplex steel 1.4462 can be used in all situations where austenitic types in the Figure would be used for corrosion resistance; in practice this steel is unlikely to be an economic alternative to 1.4301 type steels and one of the other leaner duplex steels would usually be more appropriate.

Designers should also be aware that factors other than simply the alloy content have an effect on corrosion performance. These include:

- The quality of surface finish.
- The presence of welds and heat tint around welds.
- Contamination of the surface with debris from other materials, most notably carbon steel swarf.

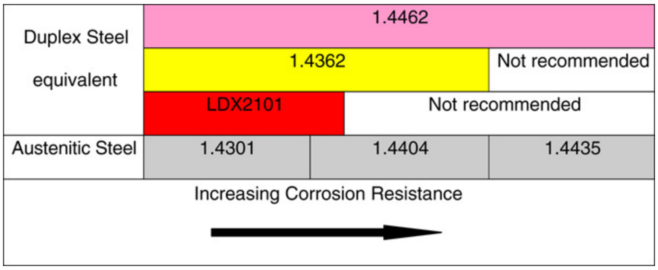

Fig. 2. Comparative ranking of corrosion resistance of austenitic and duplex stainless steels.

6. Recent examples of the use of stainless steels in structural engineering

There have been an increasing number of significant structural uses of stainless steels since the year 2000. These have tended to be signature structures where the stainless steel has been used for reasons of aesthetics, corrosion resistance, long term durability (freedom from maintenance) or a combination of these factors as well as the structural requirements. Table 4 provides some examples of these structures where stainless steels have been used for the main, if not entire, structure.

The structures given in Table 4 have used a wide range of product forms including:

- Hot rolled plate ranging from approximately 8 to 80 mm thickness that have been formed to shape and/or welded.
- Large diameter tubes either direct from a tube mill or fabricated; both straight and formed to shape.
- Circular, square and rectangular hollow sections (diameter or width/depth up to about 75 mm).
- Fabricated straight and tapered box sections made from plate.
- Investment and sand cast components.

In structural engineering it not just the availability of sections or shapes that is important in design and construction but also the ability to connect these together using technologies and methods that the construction industry is familiar with. In general the connection of parts on the structures given in Table 4 has been achieved by bolting and/or welding. Generally bolts are available

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Table 4
Examples of structural uses of stainless steel since 2000

Structure	Type	Date	Material
Aparte Bridge, Stockholm	Footbridge		1.4462
Puerto Arrupe, Bilboa	Footbridge Cycle Way		1.4362
Millennium Bridge, York	Footbridge Cycle Way	2001	1.4462
O'Connell Street Monument, Dublin	Monument		1.4404
The Likholefossen Bridge, Norway	Footbridge	2004	1.4162 (LDX2101)
Siena Bridge	Road Bridge	2004	1.4462
Cala Galdana, Menorca	Road Bridge	2005	1.4462
The Travellers, Melbourne	Moving Sculptures	2006	316L
US Air Force Memorial, Washington DC	Memorial	2006	316L
Westchester Memorial, New York	Memorial	2006	304L
Stonecutters Bridge Towers	Road Bridge	Current	1.4462
Holyhead Bridge	Footbridge	Current	1.4462
Siena, Italy	Footbridge	Current	1.4162 (LDX2101)
Marina Bay, Singapore	Footbridge	Current	1.4462

Fig. 3. Stonecutters Bridge, Hong Kong.

in similar sizes and with similar properties [7] to carbon steel bolts although there remain some difficulties with respect to duplex bolts and the use of stainless bolts on slip critical connections [8–11]; the resolution of these issues is possible but it remains an area requiring some specialist input. All the steels referenced in Table 4 are readily weldable using widely available processes and provided correct welding procedures are followed this method of joining should be no more problematic than for carbon steels.

It is interesting to note the predominance of duplex steels in the list given in Table 4. It is probable that duplex steels have been chosen over austenitic steels on the basis of:

- Improved strength.
- Improved corrosion resistance or comparable corrosion resistance at lower cost.
- Lower material cost.
- Lower risk of corrosion on hot rolled plates which may not be capable of the same quality of surface finish as austenitic steels.

A detailed discussion on the selection of duplex steels for the Stonecutters Bridge, Fig. 3, has been previously published in the literature [12].

It is probable that the trend to increased use of duplex stainless steels for structural applications will continue in the future for one or more of the above reasons.

Arguably the most significant influence on the use of stainless steels in structural engineering over the last 10 years has been the improved awareness of all duplex stainless steels as structural materials and the introduction of the lean duplex alloys. These lean alloy steels offer an opportunity for stainless steels to be used more widely in structural engineering due to the more competitive cost, increased price stability combined with good mechanical properties and appropriate levels of corrosion resistance. However, some care is needed as many fabricators, as well as designers, are unfamiliar with these materials and guidance on fabrication procedures is needed. Currently no such guidance exists although the general publication from IMOA [13] can be taken as a starting point provided account is taken of the characteristics of the particular lean steels.

7. Discussion — increasing the structural use of stainless steels

Without doubt the most inhibiting factors preventing the wider use of stainless steel are:

- The perceived and actual costs of the material.
- The price instability caused by AAF fluctuations.

It is these factors that often result in stainless steel being, perhaps unfairly, dismissed early in the design process. These factors are compounded by the relatively low mechanical properties of austenitic steels which can result in additional weight being required when compared to duplex stainless steels or carbon steels. There is also a suspicion that costs are built up based on a high risk factor (unknowingly related to AAF), comparison of prices with high quality finished architectural stainless steel (such as cladding and hand rails) or an assumed standard of work that is relevant to, say, food processing or the nuclear industry but not the construction sector. These are issues that the industry as a whole needs to research and address. There are additional costs related to fabrication which are, as previously stated, poorly understood and in need of detailed research.

Despite these cost related problems attitude changes are beginning to see stainless steels receive more serious consideration. These changes include:

- An increased awareness that the balance between initial cost and whole life cost is important.
- A desire on the part of owners to avoid future maintenance that is often expensive and disruptive.
- A much greater requirement for sustainable structures.

These are significant changes but they do not, of themselves, guarantee that stainless steels will be more widely used as structural materials rather that attitudes maybe more sympathetic to apparently initially more expensive materials that provide long term value for money. It is in this context that the trend towards using duplex steels and the introduction of newer lean alloys has to be seen. Many of these duplex materials are inherently more competitive than austenitic steels and may offer the potential advantage to the structural designer.

As a metallurgist the author is confident that appropriate materials selection can be made for structural applications; it is also highly probable that appropriate specifications for building and infrastructure projects can be developed to remove some of the "specialness" that often seems to surround stainless steels. This will help stainless steels become more competitive.

It is clear from the examples given in Table 4 that it is possible to design large and complex structures using stainless steels in a range of product forms structural designers are familiar with but these tend to be rather niche markets. The wider adoption of stainless steels for less high profile applications requires an increased awareness on the part of structural designers, the promotion of tools that provide the designer with a route to designs that use stainless steel in an efficient manner and are not penalised by rules developed for other materials (primarily carbon steel). Other papers presented at the SCI 2007 conference [14] show the breadth and depth of research in the area of structural design that would help promote efficient use of stainless steel

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and it is to be hoped that this research is adopted in revisions to existing design codes in the near future. The challenge here maybe in resolving the tension between more advanced analytical methods and the desire to present codes in a manner with which engineers are familiar with in relation to carbon steel.

There are other areas that perhaps now need to receive more attention from the research community and these would include:

- Connection design — using both ordinary and pre-loaded bolts.
- Further investigation of welded plate fabrications.
- Investigation of the newer duplex materials because much, but not all, research to date has concentrated on conventional austenitic type steels.

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