Journal of Constructional Steel Research ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Stainless steel in construction: A review of research, applications, challenges and opportunities

N.R. Baddoo

The Steel Construction Institute, Silwood Park, Ascot, Berkshire SL5 7QN, United Kingdom

ARTICLE INFO

Article history:
Received 19 December 2007
Accepted 4 July 2008

Keywords:
Stainless steel
Research
Applications
Structures
Sustainability

ABSTRACT

Stainless steel has unique properties which can be taken advantage of in a wide variety of applications in the construction industry. This paper reviews how research activities over the last 20 years have impacted the use of stainless steel in construction. Significant technological advances in materials processing have led to the development of duplex stainless steels with excellent mechanical properties; important progress has also been made in the improvement of surface finishes for architectural applications Structural research programmes across the world have laid the ground for the development of national and international specifications, codes and standards spanning both the design, fabrication and erection processes. Recommendations are made on research activities aimed at overcoming obstacles to the wider use of stainless steel in construction. New opportunities for stainless steel arising from the shift towards sustainable development are reviewed, including its use in nuclear containment structures, thin-walled cladding and composite floor systems.

1. Introduction

Stainless steel has many desirable characteristics which can be exploited in a wide range of construction applications. It is corrosion-resistant and long-lasting, making thinner and more durable structures possible. It presents architects with many possibilities of shape, colour and form, whilst at the same time being tough, hygienic, adaptable and recyclable.

The annual consumption of stainless steel has increased at a compound growth rate of 5% over the last 20 years, surpassing the growth rate of other materials. The rate of growth of stainless steel used in construction has been even faster, not least due to rapid development in China. It is estimated that in 2006, approximately 4 million tones of stainless steel went into construction applications worldwide, 14% of the total quantity consumed. There is considerable variation between different countries in the share of stainless steel being used in construction; in China more than 20% goes into construction, whereas in Germany the figure is less than 7% (Fig. 1).

Stainless steel has traditionally been used for facades and roofing since the 1920s. There are also early examples of it being used structurally, for example in 1925 a reinforcing chain was installed to stabilize the dome of St Paul's Cathedral, London. Nowadays, stainless steel is used in a very wide range of structural and architectural elements, from small but intricate glazing castings to load-bearing girders and arches in bridges.

This paper seeks to summarise the recent technological advances in the stainless steel industry which have had an impact on usage of stainless steel in construction. New applications which have emerged over the last 20 years are described. Areas of research needed to respond to current market and procurement challenges are discussed. Finally, new opportunities arising from the shift towards sustainable development are described.

2. Recent research and development activities enabling the wider use of stainless steel in construction

2.1. Production and fabrication

Stainless steel producers are continually developing their manufacturing processes with the aim of reducing costs, lowering emissions, shortening lead times and improving quality. These improvements have helped to control the cost of stainless steels, within the constraints set by the dependence on raw materials.

Perhaps the most significant recent advance impacting the construction sector has been the use of duplex grades for structural applications, which offer a combination of higher strength than the austenitics (and also the great majority of carbon steels) with similar or superior corrosion resistance. Table 1 compares the composition and mechanical properties of the two widely used austenitic stainless steels, 1.4301 and 1.4401, with those of three duplex stainless steels. (The ferritics in the table are discussed in Sections 3 and 4.) Duplexes have tremendous potential for expanding future structural design possibilities, enabling a reduction in section sizes leading to lighter structures. It is worth

E-mail address: n.baddoo@steel-sci.com.

0143-974X/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jcsr.2008.07.011

Table 1
Comparison of composition and mechanical properties of austenitic, duplex and ferritic grades of stainless steel

Group of stainless steel	Grade		Composition (EN 10088)			0.2% proof strength[a] (N/mm^2)	Ductility[a] (%)
	EN	AISI/ASTM	Cr	Ni	Mo		
Austenitic	1.4301	304	17.5–19.5	8.0–10.5	–	230	45
	1.4401	316	16.5–18.5	10.0–13/0	2.0–2.5	240	40
Duplex	1.4162[b]	S32101	21.0	1.5	0.3	530	30
	1.4362	S32304	22.0–24.0	3.5–5.5	0.1–0.5	450	20
	1.4462	S32205/S31803	21.0–23.0	4.5–6.5	2.5–3.5	500	20
Ferritic	1.4510	439	16.0–18.0	–	–	240	23
	1.4509	441	17.5–18.5	–	–	250	18
	1.4521	444	17.0–20.0	–	1.8–2.5	320	20

[a] Strength and ductility are for cold rolled strip.
[b] EN 1.4162 is not currently included in EN 10088.

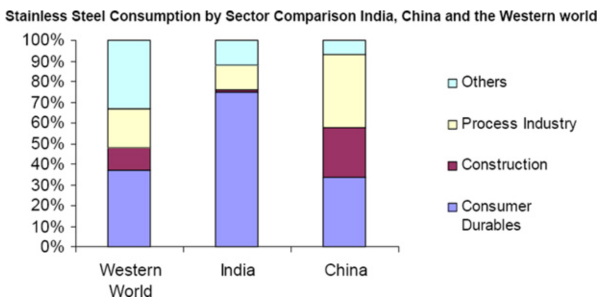

Fig. 1. Stainless steel consumption by sector in India, China and the Western World (Source: BHP Billiton and OECD).

noting that although they have good ductility, their higher strength results in more restricted formability compared to the austenitics.

The corrosion resistance of duplex grade 1.4362 is similar to that of 1.4401. The more highly alloyed 1.4462 displays superior corrosion resistance, especially to stress corrosion cracking. High nickel prices have more recently led to a demand for lean duplexes with low nickel content, such as grade 1.4162 shown in the table. The corrosion resistance of grade 1.4162 lies between that of 1.4301 and 1.4401; it currently costs slightly less than grade 1.4301.

Although usually used internally in buildings, some ferritic grades have been developed which are suitable for building envelope and structural products. For example, over the last 10 years, grade 1.4510 has been used widely in France in a tin-coated roofing system. This tin-coated finish weathers over time, gradually developing into a matt-grey patina.

Over the last 20 years, significant developments have occurred in materials processing and finishing technology, often driven by exacting architectural requirements for specific projects. The range in surface finishes has extended, ranging from matt to shiny, smooth to very rough, with combinations possible by juxtaposing finishes, adding colour etc. More finishes have become available—involving metallic and organic coatings, electrolytic and PVD (Physical Vapour Deposition) coating processes or skin passing operations. They have improved the competitive position of stainless steel compared to other high volume metallic roofing materials such as zinc, aluminium, copper and even carbon steel. The performance of the stainless finishes has also been improved in order to meet strict hygiene and cleaning requirements. Improved manufacturing processes have resulted in greater consistency of surface finish, both across a sheet and from batch to batch. Products are also now able to meet tighter dimensional tolerances.

Traditionally stainless steel welded tubes were produced by tungsten inert gas (TIG) welding. However, with the advent of reliable, high-power laser power sources, the laser beam welding (LBW) process has moved quickly into the production of stainless steel longitudinally welded tubes. The energy concentration reached in the focused spot of a laser beam is very intense and is capable of producing deep penetration welds in thick section stainless steel, with minimal component distortion. The process originally employed high capital cost equipment and its use was reserved for mass production manufacturing. However, now that more compact equipment has been developed, the use of laser welding is becoming more widespread. In addition to hollow sections, laser welded stainless steel I sections, angles and other shapes are now available (Fig. 2).

In recent years there has also been a dramatic increase in the use of laser cutting stainless steels in which a focused laser beam is used to melt material in a localised area. A co-axial gas jet is used to eject the molten material from the cut and leave a clean edge with a continuous cut produced by moving the laser beam or workpiece under CNC control. There is no tooling cost, prototyping is rapid and turn around quick. The improvements in accuracy, edge squareness and heat input control mean that other profiling techniques such as plasma cutting and oxy-fuel cutting are being replaced by laser cutting.

2.2. Design

The development of codes, standards and specifications for stainless steel as a result of research studies carried out by industry and academics has played a significant role in enabling the wider use of stainless steel in construction.

The structural performance of stainless steel differs from that of carbon steel because stainless steel has no definite yield point and shows an early departure from linear elastic behaviour with strong strain hardening. There can also be significant differences between the stress–strain curves for tension and compression. This has implications on the buckling behaviour of members and the deflection of beams. Designers require guidance on grade selection and the use of stainless steel in contact with other materials (e.g. carbon steel, reinforced concrete, masonry, timber and aluminium) in order to avoid corrosion between the dissimilar materials. Methods of connection also require specific guidance, particularly where welding is concerned, to maintain surface finish and corrosion resistance.

Prior to the development of design standards for structural stainless steel, designers were forced to conduct their own investigations or abandon stainless steel in favour of alternative materials which have proven track records and design guidance. They were required to work from first principles with an unfamiliar and costly material with unusual mechanical properties. This was an unsatisfactory situation; at best it was wasteful of the designer's time, at worst it led to misconceived design practice, misuse and either unserviceability or failure.

The Gateway Arch in St Louis, Missouri, inspired a great amount of research into the structural performance of stainless steel in the US in the early 1960s. The first American specification

Please cite this article in press as: Baddoo NR. Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of Constructional Steel Research (2008), doi:10.1016/j.jcsr.2008.07.011

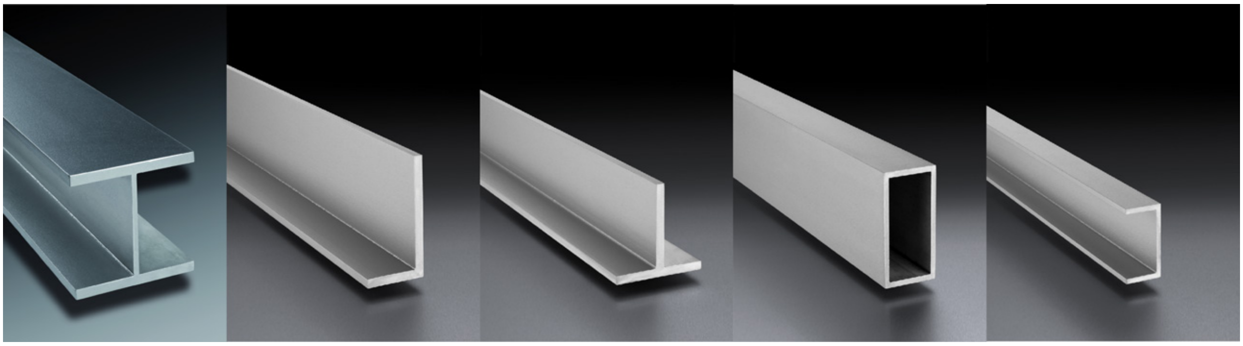

Fig. 2. Laser welded sections (Courtesy of Montanstahl AG).

dealing with the design of structural stainless steel members was published in 1968 by the AISI [1]. Following an extensive research project at Cornell University, in 1974 the specification was revised and published as the *Specification for the Design of Stainless Steel Cold-Formed Structural Members* [2], and this has subsequently been extended and updated in 1991 and 2002. Australia, New Zealand and South Africa have published approximately equivalent standards largely based on the American standard [3,4].

In 1995, the *Design and Construction Standards of Stainless Steel Buildings* were published by the Stainless Steel Building Association of Japan [5]. These specifications cover the design of welded, fabricated sections from relatively thick plate. A recent Japanese research programme studied the behaviour of lightweight stainless steel members and the *Design Manual of Light-Weight Stainless Steel Structures* was subsequently published in 2005 [6].

Between 1989 and 1992, SCI carried out a research project to develop European guidance in the areas of material selection, design, fabrication and maintenance to ensure the safe and proper application of steel in construction. The project included forming a properties database, materials tests, member and connections tests, analysis of results, design recommendations and worked examples. The resulting guidance was published by Euro Inox in 1994 as the *Design Manual for Structural Stainless Steel* [7]. Subsequently the draft pre-standard Eurocode 3 Part 1.4, giving rules for the design of structural stainless steel, was published in 1996, closely based on the Design Manual.

A European research project between 1997 and 2000 carried out a further programme of tests and analyses into the performance of structural stainless steel [8]. The results of the project were incorporated into the Second Edition of the Design Manual, published in 2002, with an extended scope including circular hollow sections and fire resistant design. A further European research project studied the behaviour of high strength structural members made from cold worked stainless steel through further tests and analyses between 2000 and 2003 [9]. The results were included in the Third Edition of the Design Manual, published in 2006. The same year, Eurocode 3: Part 1.4 (EN 1993-1-4) was issued as a full European Standard [10]. Its contents are aligned with the Design Manual, with the exception of the guidance on fire resistance where the Design Manual presents a less conservative approach. A Commentary to the Design Manual has also been prepared as a separate document which explains the basis of the recommendations and presents the results of relevant test programmes [11].

In a fire, austenitic stainless steel columns and beams generally retain their load-carrying capacity for a longer time than carbon steel structural members. This is due to their superior strength and stiffness retention characteristics at temperatures above 500 °C (Fig. 3). SCI has coordinated a $3\frac{1}{2}$ year research project studying the behaviour in fire of a range of structural stainless steel solutions through testing and numerical studies. The project included fire

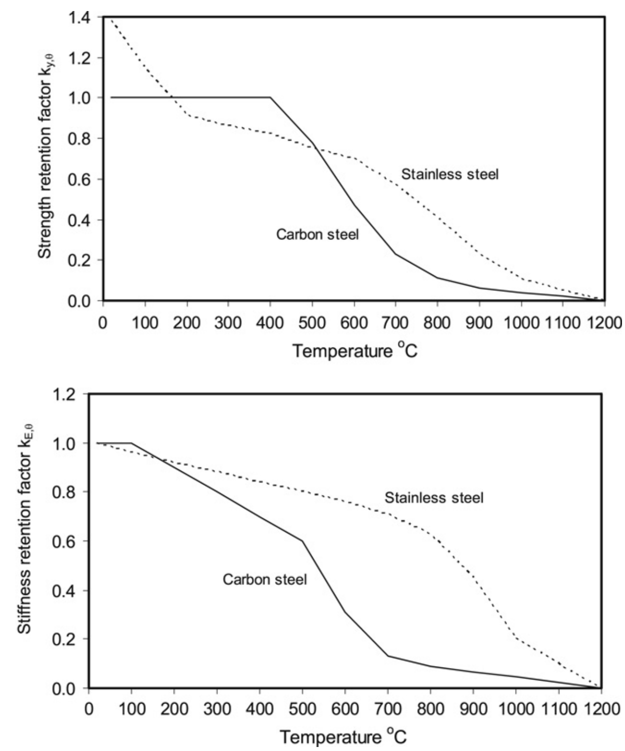

Fig. 3. Comparison of stainless steel and carbon steel strength and stiffness retention factors (grade 1.4301 stainless steel, strength at 2% strain for both stainless and carbon steel).

tests on stainless steel and concrete composite columns and beams, separating structures and load-bearing systems designed to retard the temperature rise. Slender hollow sections were also studied. The final report is due to be published in 2008 [12].

In addition, valuable research activities at Imperial College, London and other universities around the world have studied a range of relevant aspects of the structural behaviour of stainless steel; these are summarised by Gardner [13].

Stainless steel is an ideal material for explosion-resistant structures because it has high strength, good energy absorption characteristics and high ductility. The shape of the stress–strain curve in the plastic range ensures higher plastic moment resistance than carbon steel of equivalent strength. Strain-rate sensitivity is more pronounced in stainless steels than in carbon steels, i.e. a proportionally greater strength can be realised at fast strain rates for stainless steel than for carbon steel, particularly in the region of the 0.2% proof strain. Research programmes over the last 20 years have sought to quantify these strain rate effects in austenitic and duplex stainless steels and developed guidance for the design of stainless steel in blast-resistant structures [14].

Please cite this article in press as: Baddoo NR. Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of Constructional Steel Research (2008), doi:10.1016/j.jcsr.2008.07.011

Complementary to these design standards, significant standards and specifications dealing with welding, fabrication, and erection such as AWS D1.6, EN 1011-3 and EN 1090 have also been developed over the last 20 years [15–17].

2.3. Market development

In recent years, stainless steel development associations across the world have played a major role in promoting the use of stainless steel in construction. They have funded work required to transform research reports into user-friendly design guides and tools, thereby effectively disseminating design and fabrication knowledge. Through case studies, education materials, conferences and seminars, development associations have raised awareness of the potential of using stainless steel in many construction applications. Their role becomes increasingly important in the face of very effective promotional activities by competitor materials, such as aluminium and fibre reinforced plastics.

In Europe and Japan, development associations have organized demonstration stainless steel buildings, for example a steel manufacturer's research laboratory in Osaka was constructed in stainless steel to facilitate the inclusion of stainless steel into Japanese structural design codes. The building's stainless steel beams were undamaged following the nearby earthquake in Kobe in 1995.

Over the last 20 years, a number of stainless steel service centres have been established worldwide. The requirements for the building sector often concern 'exotic' products, such as patterned finishes or logistically complicated delivery forms (small 0.40 × 600 mm wide coils for rooflayers to drag on roofs), which are not the product mills' core business. Investment by mills and independent parties in downstream integrated service centres has helped overcome some of the obstacles encountered in the process of procuring stainless steel for use in the construction industry.

3. Expansion of construction applications over the last 20 years

Prior to the 1980's, stainless steel construction applications tended to be in minor building components such as lintels, wall ties, floor plates and angles and for prestige cladding. However, over the last 20 years the range of different applications has proliferated; the following section describes some of the new applications which have recently emerged.

3.1. Buildings

There have been a number of examples of the transfer of technologies developed for industrial structural applications (such as water treatment, flood barriers/gates, equipment supports, platforms/stairs and aerospace) to other industries. For example, high strength stainless steel rod technologies developed in the aerospace industry were transferred to the manufacture of yacht rigging and subsequently used in the Louvre Pyramid glass curtain wall. This led to further projects, including very large glass curtain walls, using internal or external stainless steel tension rods, cables and hollow sections to support glass façades with minimum visual impact. Stainless steel glazing fixings are typically four point or two point castings designed to connect the glass to the supporting structure. The star/spider connectors are usually grade 1.4401 solid stainless steel lost wax investment castings. Incorporated in the spider are three main movement features that give the glass freedom to move with the forces of nature.

Over the last 20 years the use of stainless steel for stone anchoring systems and masonry support has grown, as has the widespread use of stainless steel fasteners and tie systems for all types of timber products.

There has been considerable growth in the use of stainless steel in non-visible applications in buildings such as plumbing and HVAC equipment, particularly in Scandinavia, Germany and Italy. In Switzerland, the ferritic grade 1.4521 has recently been accepted by the national standards body as a suitable material for plumbing, in addition to other austenitic grades. Efficient jointing methods such as press fitting help contain installation costs. Reduced maintenance costs over the life cycle can result in stainless steel being competitive with copper, or even plastic pipework.

3.2. Infrastructure

Over the last 20 years, sizeable infrastructure and urban renewal projects in emerging markets such as China and India have led to many stainless steel applications. In airports, railway and bus stations and shopping centres, stainless steel has been used for roofs, railings, dividing partitions, stairways, escalators and barriers. Seating in public areas, playground equipment and other urban furniture is also increasingly being made from stainless steel.

Although stainless steel railings have been used for many years, over the last 20 years there has been a broad realization that they offer long term cost savings, reduced liability and aesthetic benefits. For example, one of New York's new subway lines will have 16 miles of stainless railings along the maintenance walkways that adjoin the tracks; this is strictly for long term worker protection as these areas are closed to the public.

The use of stainless steel reinforcing bars (rebar) and associated products has increased significantly in recent years, although there are examples of it being used much earlier. For example, the Progreso Pier in Mexico was constructed in the 1940s using 200 tonnes of stainless steel rebar and shows no indications of deterioration. Stainless rebar extends the lifetime of concrete structures in corrosive environments and decreases the demand for inspection and maintenance. It has been used in highway bridges, car parks, coastal facilities and other structures. In addition to improved corrosion resistance, austenitic stainless steel reinforcing can be supplied in the non-magnetic condition and this has led to its use in military, medical and scientific applications. Two design standards have been developed for stainless steel rebar; BS 6744 and ASTM A955/A995M [18,19]. A European standard is under development.

In recognition of the material's durability, attractive appearance and low maintenance requirements, a number of bridges incorporating stainless steel for the main structural elements have been built recently. Grade 1.4462 was used for the Millennium bridge footbridge (York, UK), the Cala Galdana highway bridge on the island of Menorca and the Stonecutters bridge towers in Hong Kong. Grade 1.4362 was used for the Padre Arrupe Bridge linking the Guggenheim Museum to the University of Deusto in Bilbao and for the Celtic Gateway footbridge in Holyhead, UK (Fig. 4). Grade 1.4162 was used for the Siena bridge in Ruffolo. Stainless steel cladding was also used along the outer edges of the deck of the Tsing Ma Bridge in Hong Kong in order to control air flow across the deck (wind loading was the critical design condition on this bridge, the longest combined road and rail span in the world).

Security-related applications of stainless steel, such as bollards and barriers, have also increased over the last 20 years. Blast walls on offshore topside modules to protect personnel and plant from explosions are now often made from corrugated stainless steel sheet of grade 1.4401 or 1.4362.

Please cite this article in press as: Baddoo NR. Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of Constructional Steel Research (2008), doi:10.1016/j.jcsr.2008.07.011

Fig. 4. Celtic Gateway footbridge in Holyhead, UK (Courtesy of Outokumpu).

4. Research in response to market and procurement challenges

4.1. High nickel prices

Nickel is subject to considerable price fluctuations due to stock market factors. In the last few years, the nickel price has increased, peaking at unprecedented levels, which greatly affected the cost of austenitic grades of stainless steel (typically containing 8% nickel), and duplex stainless steels (containing between 1 and 6% nickel), though to a lesser extent.

The high cost of stainless steels justifies further research into the use of greater design strengths. It is widely accepted that the 0.2% proof strength of austenitic stainless steels tends to exceed the minimum specified values given in material standards by a large margin (approximately 25%–40%), particularly for thinner material. For substantial orders, advance consultation with steel producers may well result in the guaranteeing of additional strength at no extra cost. However, for smaller orders this is not always possible and research into the possibility of raising the traditional baseline design strength for the common austenitic grades of 220 N/mm^2 to 280–300 N/mm^2 would be tremendously worthwhile.

Investigations into ways of exploiting the 'free benefits' of cold working in the manufacture of sections from austenitic grades would also be valuable. Evidence shows that 10%–25% improvements are achievable in section capacity. Exploitation of this lies in the hands of the manufacturers of the sections, who are able to balance their specification of input material against their process route to achieve consistent properties.

As a result of high nickel prices, interest in more price-stable grades has increased dramatically. The cost of ferritic grades of stainless steel is lower and more stable than that of the austenitic and duplex stainless steels as they are not alloyed with nickel. Traditionally, ferritics have been known for their moderate corrosion resistance and poor fabrication properties. However, recently developed high performance ferritic grades such as 1.4509 and 1.4521 (Table 1) can be formed to more complex shapes and joined using most conventional joining methods, including welding (up to 2 mm thickness). The resistance of ferritic grade 1.4521 to localised corrosion is at least equal to that of austenitic grade 1.4401, whereas that of 1.4509 is similar to grade 1.4301. The price of these ferritics is currently about 60%–70% of the price of grade 1.4301.

Ferritics are magnetic with lower thermal expansion than austenitics and higher thermal conductivity, meaning they conduct heat more evenly than austenitics. They are easier to cut and work than austenitics, and significantly less prone to springback during cold forming. Ferritics have higher yield strength than most austenitics and are not prone to stress corrosion cracking. The same surface finishes can be applied to ferritics as to austenitics. They have been used in a number of applications in the construction sector, such as emergency housing, factories, roofs and roof support, tunnel lining, cladding and urban furniture, particularly in Japan where the ferritic market is most developed.

The long term behaviour of these high performance ferritics as structural members and in the building envelope needs to be studied. In addition to guidance for designers on structural response, fabricators also need best practice information on forming and joining techniques. Work is needed to include these grades, and the lean duplex 1.4162, into design standards such as EN 1993-1-4.

4.2. Supply chain issues

The lack of a standardised family of sizes for stainless steel structural sections is a significant barrier to the wider use of stainless steel in construction. Designers generally have the expectation that stainless steel will be available in the same sizes as carbon steel members. The reality is quite different. Hollow sections are available in a wide range of sizes, with each manufacturer tending to stock its own selection. Channels and angles tend to be produced by roll forming (rolling or bending) and are frequently made to order. The availability of laser welded I sections and other structural sections is increasing. Not surprisingly, this situation has led to widespread confusion amongst construction specifiers about how to procure stainless steel sections. Collaborative effort is required amongst producers of stainless steel sections to move towards standardizing the range of sizes of stainless steel sections. In the meantime, an international database of available sections would inform designers what can be procured as well as giving them an appreciation of the wide range of available shapes and sizes of sections.

There is evidence of steelwork contractors charging unduly high fabrication and installation costs for stainless steel fabrications. The reason for this is sometimes unintended over-specification by the designer, i.e. an architectural surface finish for a high profile cladding panel being specified for a structural component. To overcome this problem, standard fabrication and erection specifications should be developed for different types of application to ensure that the requested level of workmanship and quality is appropriate for the application.

5. New opportunities for stainless steel arising from the pursuit of sustainable development

5.1. Nuclear power generation

A number of factors currently weigh in favour of increased nuclear power generation. Firstly, the higher world market price for fossil fuels, largely driven by sustained demand, has put nuclear power on the agenda of many countries. Nuclear power plants have a 'front-loaded' cost structure, i.e. they are relatively expensive to build but relatively inexpensive to operate. The low share of uranium costs in total generating costs protects plant operators against resource price volatility. Secondly, strengthening a country's energy supply security is best achieved by increasing the number and resiliency of energy supply options; for many developing countries, expanding nuclear power would increase the diversity of energy and electricity supplies. Thirdly, environmental considerations weigh increasingly in favour of nuclear power. Nuclear power at the point of electricity generation does not produce any emissions that damage local air quality, cause

Please cite this article in press as: Baddoo NR. Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of Constructional Steel Research (2008), doi:10.1016/j.jcsr.2008.07.011

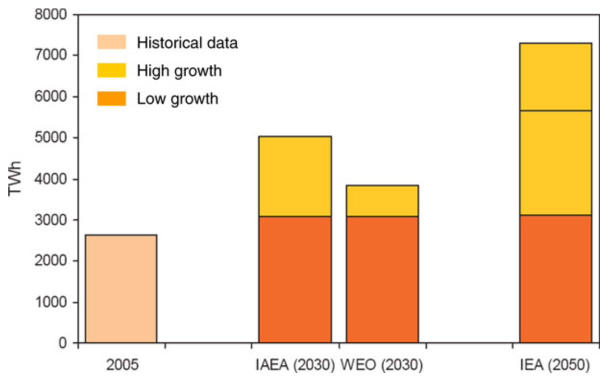

Fig. 5. Global nuclear electricity generation in 2005 and the ranges of projections for 2030 and 2050 (Four IEA scenarios cluster around the level of the black bar in the 2050 figure).

regional acidification or contribute to climate change. And finally, there are positive statements and newly-expressed interest from governments around the world.

Worldwide, at the beginning of 2007, there were 435 nuclear power reactors in operation, totalling 367 GWe (gigawatt electrical) of generating capacity. In 2005, nuclear power supplied about 16% of the world's electricity. In 2006, updated projections of nuclear power expansion to 2030 were published by the IAEA [20], and by the IEA in its World Energy Outlook 2006 [21] and a further study extended these predictions to 2050 [22]. Fig. 5 show these projections, which consider a range of scenarios covering a number of drivers such as introduction of measures to reduce CO_2 emissions and improve energy security.

There are numerous applications for stainless steel in nuclear power generation. Significant opportunities exist in the reactor building structure. For example, the use of modular double skin composite stainless steel-concrete-stainless steel containment structures can reduce construction time and enable thinner construction than would otherwise be required using reinforced concrete. The reduced construction time can often prove vital to the commercial viability of nuclear power generation, given the financial front-end loading associated with nuclear power. The structural performance of the double skin composite system needs further verification with respect to both static and explosion loading. Practical construction issues regarding filling large volumes with concrete, shrinkage and joining large panels need further research.

Other applications include stainless steel reactor vessels and vessel liners, pressure channels, fuel cladding, heat exchanger and condenser tubes and fuel pool liners. Opportunities also arise as a result of the long-term geological disposal that is being looked into by many countries. This involves disposing waste in rock, clay or salt 500–1000 m deep. The waste is first immobilised through the process of encapsulation or vitrification, then sealed by welding in a canister made from stainless steel or copper and finally buried.

5.2. Solar power generation

Solar energy can be harnessed to generate electricity using photovoltaic (PV) cells. Framed PV racks can be attached onto the cladding of a building or PVs can be integrated into the building envelope system. The durability, strength and toughness of stainless steel make it an ideal substrate material for an integrated PV building envelope system, however it is not clear whether these advantages can justify the additional cost as the design life of PV systems tends to be limited to 20 years by the functionality of the PV strips rather than by the durability of the substrate.

Solar thermal panels make use of solar energy to heat water or air for domestic hot water and space heating needs. Solar thermal collectors may be installed flush with roof tiles or inclined on supports. Stainless steel has been used both for the panel frames and for the unglazed collectors, as well as the flexible connectors and the exchanger. Stainless steel thermal collectors are available integrated into a weather resistant roof system. Dark surfaces are generally more efficient at absorbing a higher proportion of the incident solar energy than bright metallic surfaces, which tend to reflect solar radiation. Therefore, in order to improve the heat absorption characteristics of a stainless steel thermal panel, a black chrome coating is applied to the exterior face which increases the cost of the system. Research is needed into developing cheap, durable dark coatings for applications where high absorptivity are required.

5.3. Biofuel power generation

A biofuel is a fuel made from living things, or from the waste they produce. In recent years, the term biofuel has come to mean the ethanol, diesel or other liquid fuels made from processing plant material crops including corn, sugarcane and rapeseed. The most common use for biofuels is in automotive transport, for example E10 fuel. Biofuels are used globally and their use is expanding in Europe, Asia and the Americas due to rising oil prices, concerns over the potential oil peak, greenhouse gas emissions, rural development interests and instability in the Middle East. Production of ethanol doubled globally between 2000 and 2005, with biodiesel output quadrupling. The European Union has a target for 2010 that 5.75% of transport fuels should come from biological sources, but the target is unlikely to be met.

The growth in demand for biofuels presents significant opportunities for stainless steel because of its corrosion resistance. It has already been extensively used in the construction of existing biofuel industrial plants. A typical biofuel facility comprises reactors, cooling towers, boilers, process pipe, process and utility pumps, storage tanks and heat exchange coils and will use many hundreds of tonnes of stainless steel sheet, plate and pipe. Grade 1.4301 has previously been used in these plants but in the last couple of years, duplex grades 1.4362 and 1.4162 have also been specified.

5.4. Sustainable building envelopes

The need for energy-conserving buildings is high on the agenda for change in construction; most EU countries are introducing new national regulations to comply with the European Directive *Energy Performance of Buildings*. The energy efficiency of buildings can be improved through the development of improved building envelope systems with increased levels of thermal insulation and airtightness. Traditionally, improved thermal insulation meant thicker external walls, which is undesirable in modern commercial buildings striving to maximise the net to gross floor area to achieve higher rental value. However, stainless steel cladding systems used in conjunction with modern insulation systems, particularly those based on low cost nano-technology such as vacuum insulation, can provide very high levels of thermal insulation (4–6 times greater per unit thickness) than conventional foams. The life cycle cost benefits of thin wall technology are profound and easily justify technology even if the cost of cladding systems is slightly greater than conventional systems.

Vacuum technology is a rapidly maturing technology and is now commonly used in the medical industries, in packaging, transport containers and for insulation beneath slabs for roof terraces. Stainless steel is the ideal material to cover vacuum insulated panels owing to its durability and its low conductivity in comparison to that of carbon steel (the conduction at panel joints

Fig. 6. Exposed stainless steel floor decking at the Luxembourg Chamber of Commerce.

between the inner and outer panel skins has to be minimised as this can reduce the effective insulation of panels very considerably).

The ideal commercial cladding solution would comprise stainless steel, vacuum insulated panels of as large a size as possible in order to minimise the ratio of edge length to face area, designed in such a way that the panels span between floor edges without significant additional structure. This is achievable but significant development work is required, for example in order to develop edge conditions to control thermal conduction whilst achieving connection of the panel forces, air tight joints and required levels of strength and stiffness. No existing systems are available, though research and development work in this area is progressing [23–25].

5.5. Sustainable flooring systems

In the commercial building sector, it is possible to use the thermal capacity of the floor slab to regulate temperatures by passing cold night-time air under the slab to cool it and to extract warm day-time air. This can be achieved in composite slabs by using the exposed area of the decking and the heat transfer to the metal surface. Similarly water-cooled slabs have been developed which can be connected to a primary tubular structure, thereby providing both water circulation and fire resistance.

To allow good convective and radiative cooling, it is necessary for the soffit of the floor system to be exposed. For composite floor construction, this means exposing the steel decking, which is rarely done because it lacks architectural appeal. However, the stainless steel sinusoidal floor decking system used at the Luxembourg Chamber of Commerce demonstrates the attractiveness of an exposed stainless steel decking system (Fig. 6).

The quantity of heat transferred to and from the slab is increased by maximising the surface area exposed by increasing features which deviate from the horizontal plane. The trapezoidal profile of many decking sections used for composite floors in steel framed buildings can increase the surface area by 25%–50%, depending on the profile used. Radiative heat exchange, which accounts for about 50% of the heat transfer, can be maximised by ensuring that the emissivity of all surfaces is as high as possible. The low emissivity of stainless steel is disadvantageous, although the size of this effect needs to be quantified.

Research is needed to understand better the composite action between stainless steel decking and concrete floor slabs, as well as exploring the building physics performance of different decking profiles.

5.6. Renovation

Renovation, repair and maintenance of buildings accounts for 45% of all expenditure in the building construction sector across Europe, amounting to some 400 billion Euros annually. Since the rate of construction of new buildings accounts for less than 1% of the existing stock per year, very significant improvements in terms of energy saving and comfort can be made by addressing the renovation and upgrading of existing buildings.

Buildings can be over-clad and over-roofed, *i.e.* a new facade installed over the existing façade in order to improve energy efficiency, enhance comfort, arrest deterioration and improve appearance. There is potentially a large market for stainless steel for over-cladding/roofing panels as well as for the brackets and fixing systems used to connect the over-cladding back to the primary structure (the long term durability of galvanized steel in these environments is unproven) [26]. In addition, there may be opportunities for stainless steel in roof top extensions and balconies where strength, low weight and durability are required. Research is needed in order to develop over-cladding systems which significantly improve the thermal performance of a building through improved air-tightness and minimizing cold bridges. It is also necessary to understand better the environmental conditions between the old and new cladding systems, including the influence of air and moisture movement.

A recent example of stainless steel being used in renovation is the recladding of the Atomium structure in Brussels. Stainless steel provided a low maintenance and highly attractive solution, with the cost of the actual grade 1.4404 stainless steel amounting to just 2.5% of the total project cost (€25 million) [27].

6. Concluding remarks

Stainless steel offers exceptional advantages for certain applications in construction, combining intrinsic durability with aesthetics, strength, ductility and formability. Its high cost justifies ongoing research to enable maximum exploitation of its properties. Further work is required to develop guidance for construction applications on the use of economical grades of stainless steel, such as lean (low nickel) duplex and ferritic grades. The shift towards more sustainable development is opening up new opportunities for stainless steel, both in the construction of plant for energy generation and in thermally-efficient buildings. Research and development activities are required to take these ideas forward and demonstrate that stainless steel has a unique and long-term contribution to make in fulfilling human needs whilst maintaining the quality of the natural environment.

Acknowledgements

The support of the International Stainless Steel Forum, Outokumpu Research Foundation and International Molybdenum Association in the preparation of this paper is gratefully acknowledged.

References

[1] Specification for the Design of Light Gauge Cold-Formed Stainless Steel Structural Members, American Iron and Steel Institute, 1968.
[2] Specification for the Design of Cold-Formed Stainless Steel Structural Members [SEI/ASCE 8-02], [Standards No. 02-008], American Society of Civil Engineers, 2002.
[3] AS/NZS 4673:2001, Cold formed stainless steel structures, 2001.
[4] SANS 10162-4/SABS 0162-4:1997, Structural use of steel Part 4: The design of cold-formed stainless steel structural members.
[5] Design and Construction Standards of Stainless Steel Buildings Stainless Steel Building Association of Japan, Tokyo, Japan, 19955 [in Japanese].
[6] Design Manual of Light-Weight Stainless Steel Structures, Stainless Steel Building Association of Japan, Tokyo, Japan, 2005 [in Japanese].
[7] Design Manual for Structural Stainless Steel First Edition, Euro Inox, 1993 second edition, Euro Inox and The Steel Construction Institute, 2002 third edition, Euro Inox and The Steel Construction Institute, 2006.

[8] Development of the use of stainless steel in construction Final report, Directorate-General for Research, European Commission, Technical Steel Research EUR 20030 EN, 2001.
[9] Structural design of cold worked austenitic stainless steel Final report, Directorate-General for Research, European Commission, Technical Steel Research EUR 21975 EN, 2006.
[10] EN 1993-1-4:2006 Eurocode 3. Design of steel structures: General rules. Supplementary rules for stainless steels, CEN, 2006.
[11] Commentary to the Third Edition of the Design Manual for Structural Stainless Steel, downloadable from www.steel-stainless.org/designmanual.
[12] Stainless steel in fire, Final report, Directorate-General for Research, European Commission, Technical Steel Research, 2008 (in press).
[13] Gardner L. The use of stainless steel in structures. Progress in Structural Engineering and Materials 2005;7(2):45–55.
[14] FABIG Design guide for stainless steel blast walls, (Fire and Blast Information Group Technical Note 5), The Steel Construction Institute, 1999.
[15] AWS D1.6/D1.6M:2007 Structural welding code - stainless steel. 2007.
[16] BS EN 1011-3:2000 Welding. Recommendations for welding of metallic materials. Arc welding of stainless steels.
[17] prEN 1090—2 Execution of steel structures and aluminium structures. Technical requirements for the execution of steel structures, April 2005.
[18] BS 6744:2001: Stainless steel bars for the reinforcement and use in concrete—Requirements and test methods.
[19] ASTM A955/A995M: 2004 Stainless steel reinforcing bar.
[20] International Atomic Energy Agency, Energy, Electricity and Nuclear Power Estimates for the Period up to 2030, Reference Data Series No. 1, IAEA, Vienna, July 2006.
[21] International Energy Agency, World Energy Outlook 2006, IEA, Paris, 2006.
[22] International Energy Agency, Energy Technology Perspectives: Scenarios & Strategies to 2050, IEA, Paris, 2006.
[23] The Next Generation of Insulating Materials: Vacuum Insulation and 2] Vacuum Insulated Constructions in Detail, Wolfgang M. Willems, Univ.-Prof. Dr.-Ing. habil. And Kai Schild, Dr.-Ing, 7th symposium on Building Physics in the Nordic Countries. 2005.
[24] Development of vacuum insulation panel with stainless steel envelope Hoogendoorn, High performance thermal insulation—Vacuum insulated products, EMPA, January 22–24, 2001.
[25] Simmler H, Brunner S. Vacuum insulation panels for building application. Basic properties, aging mechanisms and service life. Energy and Buildings 2005;37: 1122–31.
[26] Helzel M. New meets old—Stainless steel in renovation and renewal. Euro Inox Building Series Vol 12, Luxembourg, 2007.
[27] Helzel M. Renovation of the atomium in Brussels. Euro Inox, Luxembourg, 2007.

Please cite this article in press as: Baddoo NR. Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of Constructional Steel Research (2008), doi:10.1016/j.jcsr.2008.07.011