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Structural Performance of Stainless Steel Reinforced Concrete Members: A Review

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Abstract

Degradation of reinforced concrete (RC) infrastructure because of corrosion of the steel reinforcement is a well-known and expensive global problem. The inspection, repair, maintenance and replacement costs are a huge drain on resources, while the consequent disruption damages productivity. Existing measures to improve the performance of failing RC structures are generally retrospective and do not aid the sustainability agenda, nor do they effectively reduce the maintenance requirements over the remaining design life of the structure. In light of this, the replacement of traditional, corrodible, carbon steel reinforcement with inherently corrosion-resistant stainless steel reinforcement in the design of concrete structures and infrastructure is a viable and attractive solution. There has been a rapid increase in interest in this topic in recent years from the engineering research community, mainly owing to the growing problem of aging and deteriorating infrastructure as well as the lack of available and appropriate performance data and design guidance for stainless steel reinforced concrete. This paper presents a state-of-the-art review of stainless steel reinforced concrete, both at a material and structural level and assembles and thoroughly reviews the known information as well as identifying the key gaps. The paper is aimed at both the research community, to drive future research agendas, as well as practicing engineers so they can employ sustainable and maintenance-free stainless steel reinforced concrete more readily and with confidence.

Keywords: State-of-the-art review, Stainless steel reinforcement; Reinforced concrete members; Continuous strength method, International design standards.

Highlights

- The paper presents a thorough review of the existing knowledge on stainless steel reinforced concrete structural members.
- Stainless steel reinforcement is typically used for applications where its corrosion resistance and long life cycle is desirable. It is becoming more popular in place of carbon steel reinforcement as its low-maintenance and excellent performance is increasingly desirable in response to ever-rising sustainability targets.
- The paper presents a detailed discussion on the material properties, as well as a discussion on existing design methods and performance data.
- Further suggestions for future research are highlighted.

1. Introduction

This paper presents a thorough review of the existing information on the use of stainless steel reinforcement in concrete structures, for improved durability and structural performance. Reinforced concrete (RC) structures are widely used for a range of structural applications such as multi-storey buildings, tunnels and bridges owing to the efficient use and ready availability of the constituent materials. Traditionally, and most commonly, RC structures comprise carbon steel reinforcing bars or mesh surrounded by concrete. There have been a range of advancements in recent years in terms of these constituent materials, both for the reinforcement as well as the concrete. One such development has been the increased use of stainless steel (SS) reinforcement in place of carbon steel bars to improve the overall performance, especially in terms of durability and a maintenance-free service life, as well as in response to growing demands for structures to be built in a more sustainable manner. In addition, SS reinforcement has been utilized for rehabilitation and restoration purposes including historical buildings and repairing corroded RC elements (e.g. [1-3]). It has been recognised that the use of SS reinforcement is an efficient method for preventing corrosion in RC structures over a long life-cycle [4-6], which is an increasingly important attribute as there are large volumes of aging infrastructure around the world.

Corrosion of carbon steel (CS) reinforcement is the primary cause for deterioration in concrete structures. It results in cracking and spalling of the concrete cover as well as serious structural problems in harsh environments [7, 8]. Even in conditions which previously may have been considered “normal” or not particularly severe, corrosion of reinforcement is a huge issue with increased use of de-icing salts, greater levels of pollution and higher in-service loading than originally designed for. Thus, there are increasing demands to improve the durability and service life of RC structures mainly because of the significant costs associated with maintenance, inspections, repairs as well as the expenses associated with a structure being out of service [9, 10].

Incorporating SS reinforcement in structural concrete can reduce the life-cycle costs and offer a more durable long-lasting alternative to traditional carbon steel. There are other methods which are used by engineers to improve the corrosion resistance of RC structures such as using sealants or membranes on the concrete surface, increasing the concrete cover, and using cement inhibitors or reinforcement coatings [11, 12]. However, in extreme corrosive environments, these measures may not prevent the development of unacceptable levels of corrosion. Moreover, these are not particularly sustainable solutions and typically involve using more materials. In this context, stainless steel reinforcement provides an ideal and efficient solution to the deterioration and corrosion problems for exposed reinforced concrete structures [13, 14].

From a structural perspective, stainless steel reinforcement offers distinctive mechanical properties including excellent strength, ductility, stiffness, fatigue resistance and toughness and is fully recyclable at the end of its service life [15-17]. However, it is also more expensive than carbon steel in terms of the initial cost and this is one of the primary reasons that it is not specified more commonly in RC applications, and tends to be used mainly in harsh and aggressive environments. There is a preconception amongst engineers that stainless steel reinforcement is prohibitively expensive, although this does not account for the whole-life costs. For example, employing stainless steel in place of traditional carbon steel reinforcement extends the service life cycle of structures and may also significantly reduce the costs associated with expensive inspection, maintenance, monitoring and rehabilitation works [18-20].

The use of stainless steel for concrete reinforcement to improve the durability, life-span and resilience is not new [4, 5] although there is a notable lack of performance data available in the existing literature. The current design approaches do not include specific rules for stainless steel reinforced concrete, and generally suggest using the same criteria as for traditional carbon steel reinforced concrete [21]. The existing material models provided for the structural analysis of reinforced concrete members in current design standards, such as Eurocode 2 Part 1-1 [22], are not appropriate for stainless steel reinforced concrete and lead to inaccurate predictions of the section capacity [23, 24]. Given the high initial costs of stainless steel reinforcement, as well as the constant need to improve the sustainability of structures, it is essential that efficient and appropriate design guidance is made available for designers and the engineering community.

Accordingly, the motivation for this work is to present a comprehensive review of the existing available information on stainless steel reinforced concrete and to highlight the essential information required for better implementation of these materials in RC applications. In addition, the paper aims to investigate the key behavioural aspects and propose usable design guidance.

2. Stainless steel reinforcement

Stainless steel is a durable, sustainable and efficient construction material and can be used in a diverse range of applications. It has outstanding strength, toughness and ductility, as well as fatigue properties. There are various forms of stainless steel available in the market including plates, sheets, bar products and structural sections. The most common form used in load-bearing structures is bare structural sections such I-beams and hollow sections. However, the use of stainless steel reinforcement is also increasing, owing to the attributes previously mentioned, which has led to a significant increase in research in recent years.

2.1. Use of stainless steel reinforcement in concrete structures

Currently, stainless steel reinforcement is mainly specified in place of carbon steel in applications where durability is a requirement. This is often in structures and infrastructure which are in harsh environments, such as marine or industrial settings. However, stainless steel has a range of other attractive physical and mechanical properties as previously outlined which enable structures to remain in good service life, with minimal inspection or maintenance requirements, for longer periods of time compared with traditional carbon steel. The Progresso Pier in Mexico represents one of the first significant structural applications of stainless steel reinforcement, as shown in Fig. 1(a) [25]. It was constructed in the early 1940's using grade 1.4301 austenitic stainless steel and has been in continuous service for over 70 years without any major repair or maintenance activities. In the forefront of this image, the remains of a carbon steel reinforced concrete pier can also be viewed; this was built many years after the stainless steel reinforced concrete pier but has been completely destroyed owing to corrosion of the rebars. Another example which illustrates the efficiency of stainless steel reinforcement is the New Champlain Bridge in Canada which was built in 2016 using grade 1.4362 (2304) duplex stainless steel, as shown in Fig. 1(b) [26]. This bridge was built as a replacement for the original structure which experienced severe deterioration and extreme corrosion due to the use of de-icing salts and an inadequate drainage system. Stainless steel reinforcement has also been used in the construction of Stonecutters Bridge in Hong Kong (Fig. 1(c)) [27] and Sheik Zayed Bridge in Abu Dhabi (Fig. 1(d)) [28] constructed in 2009 and 2010, respectively, using grade 1.4462 duplex stainless steel.

In addition to new construction, stainless steel reinforcement has also been used for renovation and restoration purposes. For example, austenitic grade 1.4301 stainless steel reinforcement was used to rehabilitate the pillars and stone arches of the Knucklas Rail Bridge in the UK [5]. In addition, Sydney Opera House in Australia and Guildhall Yard in London were rehabilitated using grades 1.4436 and 1.4301 austenitic stainless steel, respectively [12, 29].

(a) (b)

(c) (d)

Fig. 1: Images of infrastructure built using stainless steel reinforcement including (a) The Progresso Pier in Mexico, (b) the New Champlain Bridge in Montreal, (c) the Sheik Zayed Bridge in Abu Dhabi, and (d) Stonecutters Bridge in Hong Kong.

2.2. Durability

The demands from the engineering community and governmental organisations to improve the durability and resilience of reinforced concrete structures are constantly increasing, mainly owing to the concerns and costs associated with corrosion of the reinforcement and carbonation of the concrete. The inspection, repair, maintenance and replacement costs are a huge drain on Government resources, while the disruption damages the productivity and prosperity of local regions. The UK alone currently spends in excess of £1bn annually repairing damaged concrete due to corrosion, which represents more than 3% of the entire construction industry [30]. The annual estimation of the direct costs for repairing corroded RC infrastructure is over €5 billion for Western Europe [31], and $8.3 billion for the United States [32, 33]. Moreover, 7.6% of all highway bridges in the United States were identified as being structurally deficient owing specifically to reinforcement corrosion [34].

The damage caused by reinforcement corrosion is not just limited to the economic costs. In addition, it can impair the safety and functionality of structures owing to the loss of bond between the concrete and reinforcement [35], cause a reduction in the steel area and strength, lead to corrosion-induced cracking of the concrete cover, and can result in a significant reduction in the ductility, load bearing capacity and structural stiffness of the affected members [9, 36]. In normal conditions, reinforced concrete structures are unlikely to experience significant corrosion owing to the protection provided by the concrete and its high alkalinity. However, this protection might be lost in harsh environments as a result of chloride penetration or carbonation of concrete [1], or when excessive cracking has occurred. This is typically true for structures reinforced with carbon steel and exposed to seawater or when de-icing salts are frequently required.

The typical approaches to improving the durability of reinforced concrete structures are to modify the concrete design by either adjusting the ingredients or increasing the cover distance, to use more durable reinforcement bars such as those made from fibre reinforced polymers (FRP) or stainless steel, to use sealants on the concrete surface and the surface of the rebars and/or to apply cathodic protection to the steel reinforcement. However, whilst these approaches can improve the corrosion resistance, they may not provide an inherently durable solution to the problem of chloride-induced corrosion and there is a risk that significant maintenance may be required within the design life of the structure. In this context, stainless steel reinforcement offers a durable and efficient alternative option over the conventional steel and reduces the risks of deterioration and corrosion problems [37]. In addition, the use of stainless steel reinforcement may increase the lifetime of RC structures to over 100 years [5, 31, 38-41].

The two main causes for corrosion of reinforcement in typical structures are (i) the local environment, particularly in a marine or industrial setting, and (ii) chloride penetration from using de-icing salts in frosty weather or from marine environments. The latter is often an issue for bridges in particular, and can occur in any setting, even those not necessarily characterised as harsh. At a certain level of chloride concentration, the passive protective layer on carbon steel is damaged and chloride-induced corrosion develops. Stainless steel exhibits extraordinary corrosion resistance compared with carbon steel, even in aggressive conditions, owing largely to its chromium content which contributes to the formation of a thin, self-regenerating chromium oxide film on the surface of the material in the presence of oxygen, resulting in a strong passive protective layer [42, 16]. The influence of chloride concentration and the pH value of the concrete on different grades of stainless steel and also carbon steel is shown in Fig. 2. The figure reflects the poor corrosion resistance of carbon steel when the pH of concrete is below 13, even at zero chloride concentration. On the other hand, stainless steel reinforcement has exceptional corrosion resistance even at very high chloride levels and low pH values.

It is clear from the data presented in Fig. 2 that the corrosion performance of stainless steel reinforcement is variable and dependent on many different factors including the temperature and chloride ion concentration [43-45]. The microstructure, type of alloy and chemical composition also have a significant influence on the corrosion behaviour [46-49]. For instance, duplex stainless steel rebars generally demonstrate similar or even better corrosion resistance compared to that of austenitic stainless steels [50, 51]. Several researchers have recently studied the corrosion performance of different types of stainless steel reinforcement, including austenitic and duplex grades, and compared the behaviour with conventional steel [52-54]. It was concluded that the examined stainless steel grades (i.e. grades 1.4307, 1.4404, 1.4482, 1.4362, 1.4482 and 1.4462) offer exceptional corrosion performance compared with conventional carbon steel reinforcement. The risk of reinforcement corrosion when stainless steel and carbon steel are used together has also been studied and it was shown that there is no increased risk of galvanic corrosion even when the two materials are in direct contact [1, 18, 55-57].

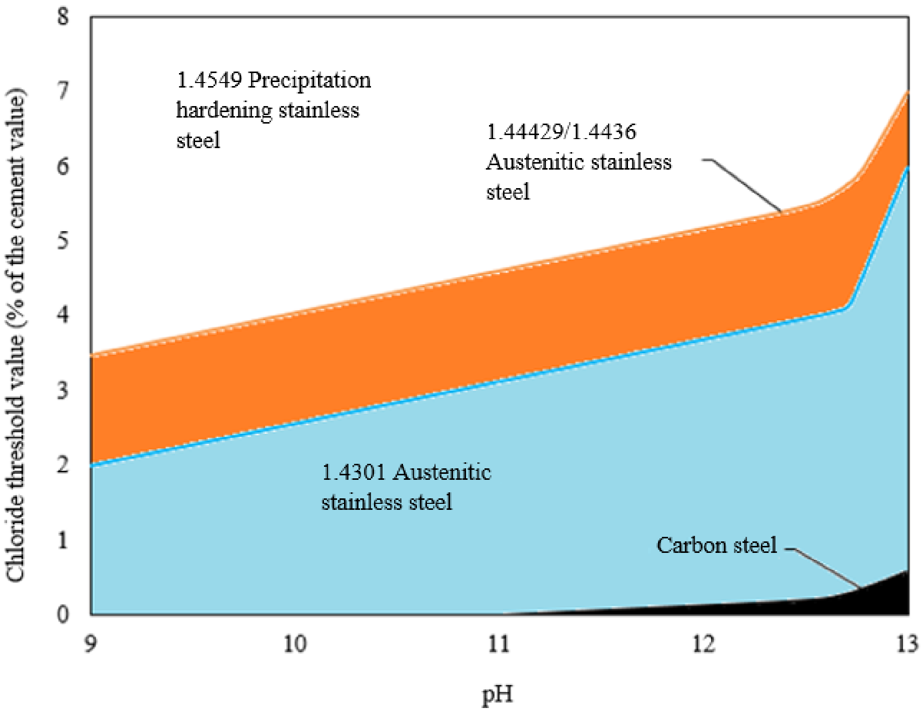


Fig. 2: Corrosion behaviour of different stainless steel reinforcements compared with carbon steels (adapted from [58]).

2.3. Life cycle costs

Reinforced concrete is used widely in all over the world as a construction material because it is efficient, economic and versatile. However, as outlined before, in recent decades RC structures have increasingly experienced structural problems as they age due primarily to durability failure, especially those subjected to aggressive environments. It is recognized that concrete structures reinforced with stainless steel have better durability performance and require less maintenance and rehabilitation works over their lifetime [59] compared with carbon steel reinforced concrete. Implementing stainless steel reinforcement in concrete structures could enable a design life which exceeds 100 years [5,31,38-41]. In highways and infrastructure, these characteristics are of great importance to avoid highway rerouting and road closures as well as the associated delays and carbon emissions. Furthermore, using stainless steel reinforcement could result in further savings owing to potential relaxation of some of the durability requirements (discussed later) including the minimum concrete cover, allowable crack widths and the need for reinforcement coating [5].

The use of stainless steel reinforcement in concrete structures is still very limited owing largely to the high initial cost which is typically between 3 and 8 times compared with that of conventional steel [4, 59, 60, 61] as well as the lack of available and efficient design guidance. This limits the use of stainless steel reinforcement to applications that are more susceptible to chloride-ingress such as coastal buildings, tunnels and bridges. Nevertheless, the relatively higher initial cost of stainless steel is offset by the durability and positive economic impact in a life-cycle cost analysis (LCCA). Stainless steel reinforcement exhibits excellent long-term performance and has lower inspection and maintenance costs associated with durability problems over the life cycle compared with carbon steel reinforced concrete [7]. In addition, limiting the use of stainless steel reinforcement to the most corrosion-prone locations in a structural element results in further utilization of the material and reduces the relatively high initial cost. This selective use approach is adopted in Design Manual for roads and bridges by the Highway Agency [62].

In recent years, as the popularity and interest in more durable construction materials has grown, the research into the life cycle costs of stainless steel reinforced concrete elements compared with carbon steel members has also increased. For example, Fig. 3 presents a comparison of the LCCAs for the construction and operation of Oland Bridge in Sweden using stainless steel and carbon steel reinforcement, respectively [5]. It is clearly observed that using stainless steel rebars results in a relatively high initial cost, as expected, but then requires no additional costs over the design live of 120 years and the life cycle costs remain constant. On the other hand, the overall costs for the carbon steel reinforced concrete solution significantly increase after around 18 years and reach very high values from approximately 25 years. Another case study on the Schaffhausen Bridge in Switzerland showed that using grade 1.4301 stainless steel reinforcement reduces the life cycle cost by 14% compared with that of carbon steel [5].

It has been shown that using stainless steel reinforcement can significantly increase the lifetime of structures and reduce the associated maintenance costs [8, 63, 64]. In fact, the use of stainless steel reinforcement in place of carbon steel rebars can reduce the overall maintenance costs during the service life by up to 50%, especially for bridges and marine structures [8]. This indicates that in spite of the higher initial cost of the bare stainless steel reinforcement, the variation on the overall construction costs may be much less significant and the whole life cycle costs may be less than if carbon steel rebars were employed. Val and Stewart [59] conducted a LCCA for reinforced concrete structures in marine environments and concluded that stainless steel reinforcement is a cost-effective option when the overall construction costs do not increase by more than 14% when stainless steel rebar is used in place of carbon steel bars.

For bridge decks in particular, stainless steel RC was shown to provide a lower overall life cycle cost (LCC) compared with carbon steel RC [65]. Another study compared the cost efficiency of bridge decks using different types of reinforcement including conventional steel and stainless steel reinforcement [66] and it was shown that using stainless steel rebars results in 52% lower overall costs compared with using carbon steel reinforcement. Mistry et al. [67] reported that the LCC for the stainless steel reinforced concrete Progresso Pier in Mexico as previously discussed was 30% lower than for the adjacent carbon steel reinforced concrete pier. Sajedi and Huang [68] conducted a LCC analysis on different materials that are typically used in the design and repair of reinforced concrete structures including conventional carbon steel, epoxy coated and stainless steel reinforcement as well as high performance concrete with either silica fume, slag or fly ash. It was shown that using stainless steel reinforcement in reinforced concrete can reduce the LCC by 32% and 19% compared with that of carbon steel and epoxy coated reinforcement, respectively. Recently, Hasan et al. [64] performed a LCCA to determine the most advantageous geographical locations relative to the coast for using stainless steel reinforcement in concrete bridges. The study showed that even for short inspection periods (i.e. 15 years), stainless steel reinforced concrete bridges exhibited lower life cycle costs compared with carbon steel reinforced concrete structures, for distances up to 2.5 km from the coastline.

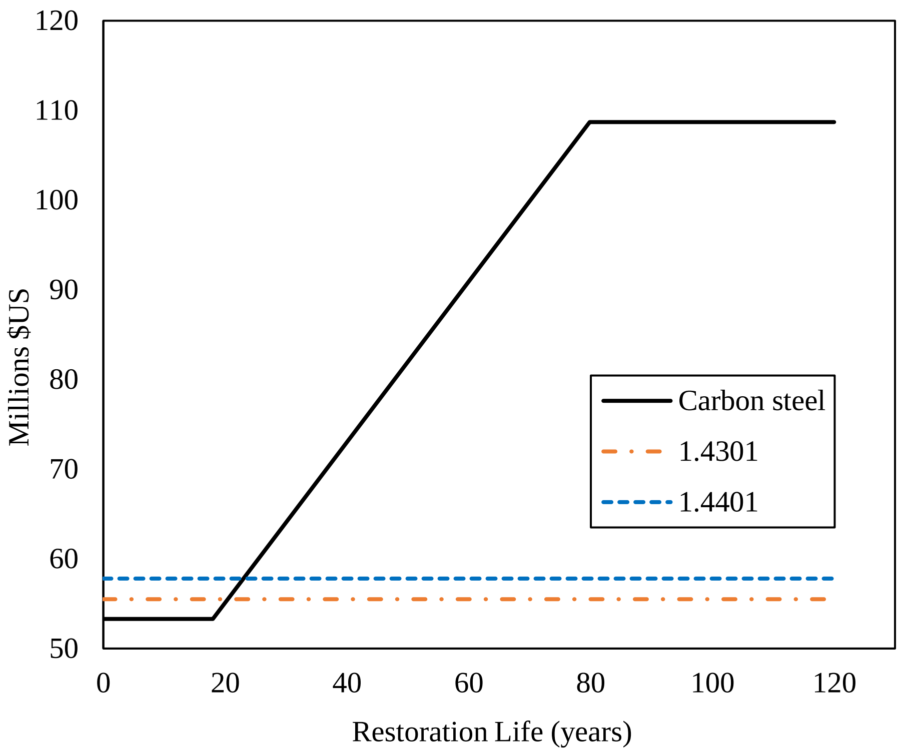


Fig. 3: Analysis of the life-cycle cost for Oland Bridge in Sweden (adapted from [5]).

2.4. Stainless steel reinforcement material properties

Stainless steel is generally categorised into 5 different families including the austenitic, duplex, ferritic, martensitic and precipitation hardening grades. Reinforcement bars are generally available in the austenitic and duplex grades only, and the most commonly available include austenitic grades 1.4301, 1.4307 and 1.4311 and duplex grades 1.4362, 1.4462 and 1.4162 [69]. Grade 1.4301 is the most commonly available stainless steel used in structural applications, and is defined by its key constituent elements of 18% chromium and 8% nickel. It is typically used in a wide variety of applications that require good corrosion resistance and excellent strength, formability and weldability. Grade 1.4307 is an alternative to grade 1.4301 which has a lower carbon content, thus improving the weldability and also the resistance to intergranular corrosion. Grade 1.4311 austenitic stainless steel is also a low-carbon material but with improved low-temperature toughness and also excellent tensile strength owing to its higher nickel and nitrogen content.

Grade 1.4362 duplex stainless steel provides superior corrosion resistance compared with the austenitic grades especially against localized corrosion and stress corrosion cracking due to the relatively high nickel content [70]. Grade 1.4462 offers similar corrosion resistance to that of grade 1.4362 but with superior mechanical strength. More recently, grade 1.4162 was developed as a new type of duplex stainless steel reinforcement which comprises a lower nickel content and therefore more competitive price [71] whilst still retaining excellent corrosion resistance and around twice the characteristic strength of austenitic stainless steels.

There are a number of stainless steel reinforcement standards available, including BS 6744 [72] and ASTM A955 [73]. These include specifications on the geometries and tolerances, production methods, chemical composition and the mechanical and physical properties, as well as guidance on durability. BS 6744 also makes frequent reference to the European material standard for stainless steel EN 10088-1 [74] which lists the chemical composition of stainless steels in accordance with their main properties including corrosion resisting steels, heat resisting steels and creep resisting steels. Clearly, given the wide range of stainless steel that are available on the market, it is important to understand the different properties, and how this affects the structural and durability performance, during material specification. Therefore, the following sub-sections present the key properties of stainless steel rebars which are important for engineers.

2.4.1 Chemical composition

Stainless steels are defined as a group of metals containing a minimum chromium content of 10.5% and a maximum carbon content of 1.2% [74]. The mechanical properties and corrosion performance for each grade largely depend on the constituent elements of the stainless steel alloy. For instance, chromium (Cr) improves the corrosion resistance of stainless steel through the development of a passive protective layer on the surface in the presence of oxygen [42]. In addition, molybdenum (Mo) improves the corrosion resistance against chloride-induced pitting corrosion while nickel (Ni) improves the ductility and the formability of the material and nitrogen (N) significantly enhances the mechanical properties of the stainless steel material including strength and ductility [31, 75]. There are a number of other alloying elements that typically exist in stainless steels such as phosphorus (P), copper (Cu), carbon (C), manganese (Mn), silicon (Si), and sulphur (S). A list for the chemical composition of the most common stainless steel reinforcement grades is provided in Table 2, in accordance with the guidance given in BS 6744 [72].

Table 2: Chemical composition of some common grades of stainless steel reinforcement in accordance with BS 6744 [72].

Stainless steel grade	Chemical composition (%) – Maximum recommended % values for each element									
	C	Si	Mn	S	Cr	Ni	Mo	Cu	P	N
1.4311	0.03	1.0	2.0	0.030	17.5-19.5	8.5-11.5	-	-	0.045	0.12-0.22
1.4436	0.05	1.0	2.0	0.030	16.5-18.5	10.5-13.0	2.5-3.0	-	0.045	≤ 0.11
1.4162	0.04	1.0	4.0–6.0	0.015	21.0–22.0	1.35–1.70	0.10–0.80	0.10–0.80	0.040	0.20–0.25
1.4362	0.03	1.0	2.0	0.015	22.0–24.5	3.5–5.5	0.10–0.60	0.10–0.60	0.035	0.05–0.20
1.4462	0.03	1.0	2.0	0.015	21.0–23.0	4.5–6.5	2.5–3.5	-	0.035	0.10–0.22
1.4404	0.03	1.0	2.0	0.030	16.5–18.5	10.0–13.0	2.0–2.5	-	0.045	≤0.11

2.4.2 Physical properties

The physical properties of the various grades of stainless steel are presented in BS 6744 [72] which refers to the relevant European standard for stainless steel [74] and these are presented in Table 3 together with those of carbon steel [76] for comparison. The most important physical properties for stainless steel reinforced concrete applications are density, coefficient of thermal expansion, thermal conductivity and magnetic permeability. The density of stainless steel reinforcement is very similar to that of carbon steel, as shown in Table 3. The majority of stainless steels including the duplex and ferritic grades are magnetic. On the other hand, austenitic alloys are generally considered to be non-magnetic although the chemical composition and manufacturing process may influence the magnetizability. For instance, the cold rolled production process might slightly increase the magnetic permeability of some austenitic stainless steel grades [31].

Austenitic and duplex stainless steels exhibit greater coefficients of thermal expansion compared with conventional carbon steel. This variation in the thermal expansion is not negligible and might be a concern for concrete structures owing to the potential for cracking in the concrete [38]. However, it was shown that the levels of tensile stresses which develop in stainless steel reinforced concrete elements due to thermal expansion are not expected to cause concrete cracking [77]. It is also noteworthy that the thermal expansion coefficient of concrete itself may vary by +/- 20% depending on the ingredients used in the mix design.

Table 3: Physical properties of stainless steel [74].

Reinforcement type	Grade	Density kg/m^3	Mean coefficient of thermal expansion between 20 ˚C and 100 ˚C: (10^6/˚C)	Thermal Conductivity at 20 °C (W/m K)	Modulus of elasticity (kN/mm^2)	Magnetizable
Carbon steel	-	8000	12	51	200	Yes
Austenitic	1,4310	7900	16	15	200	No
Austenitic	1.4301	7900	16	15	200	No
Austenitic	1.4436	8000	16	15	200	No
Duplex	1.4462	7800	13	15	200	Yes
Duplex	1.4362	7800	13	15	200	Yes

2.4.3 Mechanical properties

As previously stated, stainless steel reinforcement offers excellent mechanical properties including high strength and stiffness as well as exceptional ductility, toughness and fatigue properties. Nevertheless, these properties vary depending on the grade and the method of production. Austenitic and duplex stainless steels are the most common grades used as a reinforcement in concrete structures owing to the outstanding corrosion resistance, excellent structural behaviour, and ready availability [78, 79]. These grades generally provide greater strength, strain hardening and ductility compared with carbon steel reinforcement. Moreover, they offer a distinctly different constitutive response to carbon steel also. Fig. 4 shows that stainless steel exhibits a continuous nonlinear stress-strain response without a clear yield point and has significant levels of strain hardening and high ductility. The 0.2% proof stress ($\sigma_{0.2}$) is typically used to define the yield point. On the other hand, carbon steel shows an elastic-plastic, or elastic-linear hardening response, characterized by a well-defined yield point and moderate degree of strain hardening.

Table 4 presents the mechanical properties of some of the most common grades of stainless steel reinforcement, including the 0.2% proof strength $\sigma_{0.2}$, ultimate strength σ_u, Young's modulus E, and ultimate strain ε_u. A study into the mechanical and structural behaviour of stainless steel reinforcement showed that the ductility of austenitic and duplex stainless steel is approximately three times greater than that of carbon steel rebar [16]. The distinctive ductility property of stainless steel is of particular interest for extreme loading scenarios, such as seismic applications, as it enables structures to last longer, survive greater levels of damage and deformation and also re-distribute loads and stresses through the structure [80-83].

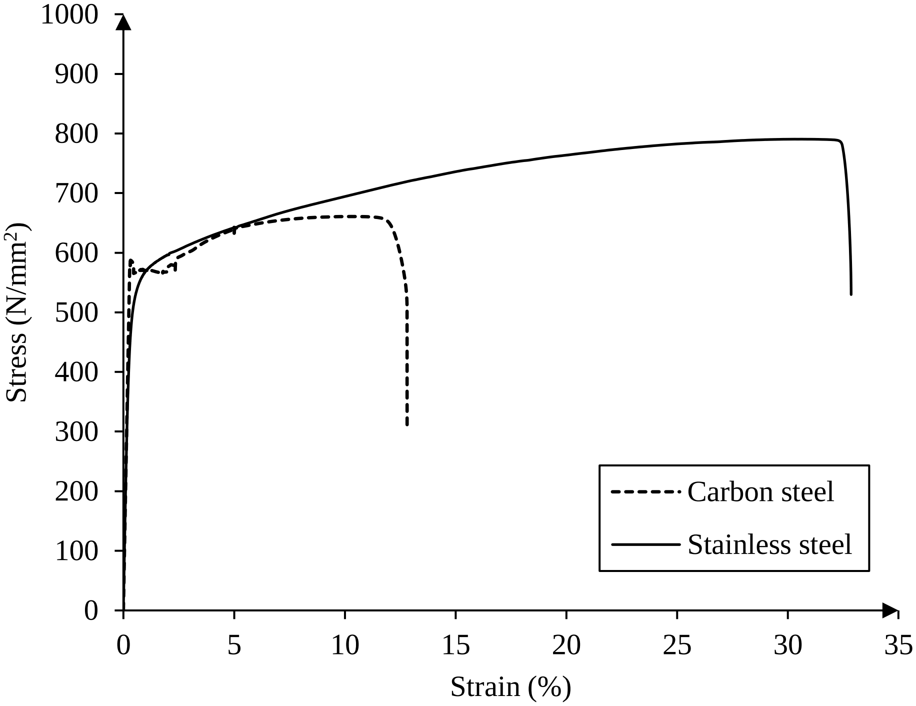


Fig. 4: Typical stress-strain curves for carbon steel and stainless steel grade 1.4301, with diameter of 10 mm (adapted from [21]).

With reference to the Young's modulus, BS 6744 [72] suggests using a value between 190-200 kN/mm^2 for different grades of stainless steel based on guidance given in EN 10088-1 [74]; for carbon steel, Eurocode 2 assumes that Young's modulus is equal to 200 kN/mm^2 [22]. However, several recent studies have shown that a lower Young's modulus value for stainless steel reinforcement may be more appropriate in design [16, 79, 84]. This is mainly because of the nonlinearity nature of constitutive behaviour of stainless steel reinforcement and is an area that requires more research, including reliability analysis, in the future.

Table 4: Mechanical properties of stainless steel and carbon steel reinforcement.

Product form	Grade	Bar diameter (mm)	$\sigma_{0.2}$ (N/mm^2)	σ_u (N/mm^2)	E (kN/mm^2)	ε_u (%)
Tested by Gardner et al. [85]	1.4307	12	562	796	210.2	39.9
	1.4307	16	537	751	211.1	42.4
	1.4311	12	480	764	202.6	48.3

	1.4162	12	682	874	199.1	32.4
	1.4162	16	646	844	195.2	32.9
	1.4311	16	528	717	199.9	47.9
	1.4362	16	608	834	171.4	35.1
Tested by Rabi et al. [21]	1.4301	10	515	790	200.9	32.4
	1.4301 ‘‘grip-rib’’	12	715	868	184.0	21.1
	Carbon steel	10	589	661	201.4	12.49
	Carbon steel	12	554	635	211.8	9.21
Tested by Rabi et al. [84]	1.4301	8	720	888	156.0	44.6
	1.4301	10	668	799	148.6	38.3
	1.4301	12	670	795	186.8	26.7
	1.4436	8	614	823	178.5	36.5
	1.4436	10	661	793	179.3	25.6
	1.4436	12	645	803	198.6	25.3
	Carbon steel	10	525	627	196	20.1
Tested by Li et al. [86]	1.4462	6.5	595	800	141.0	32.5
	1.4462	12	660	830	141.0	37.8
	1.4462	16	640	795	151.0	33.9
	Carbon steel	12	380	530	230.0	31.0
Tested by Li et al. [79]	1.4362	12	637	872	156	33.0
	1.4362	16	532	768	156	36.4
	1.4362	25	543	761	202.0	31.1
	1.4362	28	514	743	138.0	39.5
	1.4362	32	527	748	139.0	36.9

	Carbon steel	16	477	654	202.0	26.8

For design, it is important to obtain a reliable and usable material model, which is capable of capturing the key material properties and reflecting the true material behaviour. As stated before, the stress-strain response for carbon steel is distinctly different to that of stainless steel, and can be readily simulated using a straight-forward bilinear response, which is not appropriate for stainless steel. The constitutive stress-strain behaviour of stainless steel is typically represented using the modified Ramberg-Osgood material model, which provides a continuous and nonlinear function. The original version of this model was first proposed in 1943 [87] and reflects the elastic stage of the response and later modifications were developed to capture the inelastic stage [88, 89]. The modified Ramberg-Osgood material model is widely used for capturing the response of stainless steel in design and simulation and it is determined using Eqs. 1 and 2, respectively:

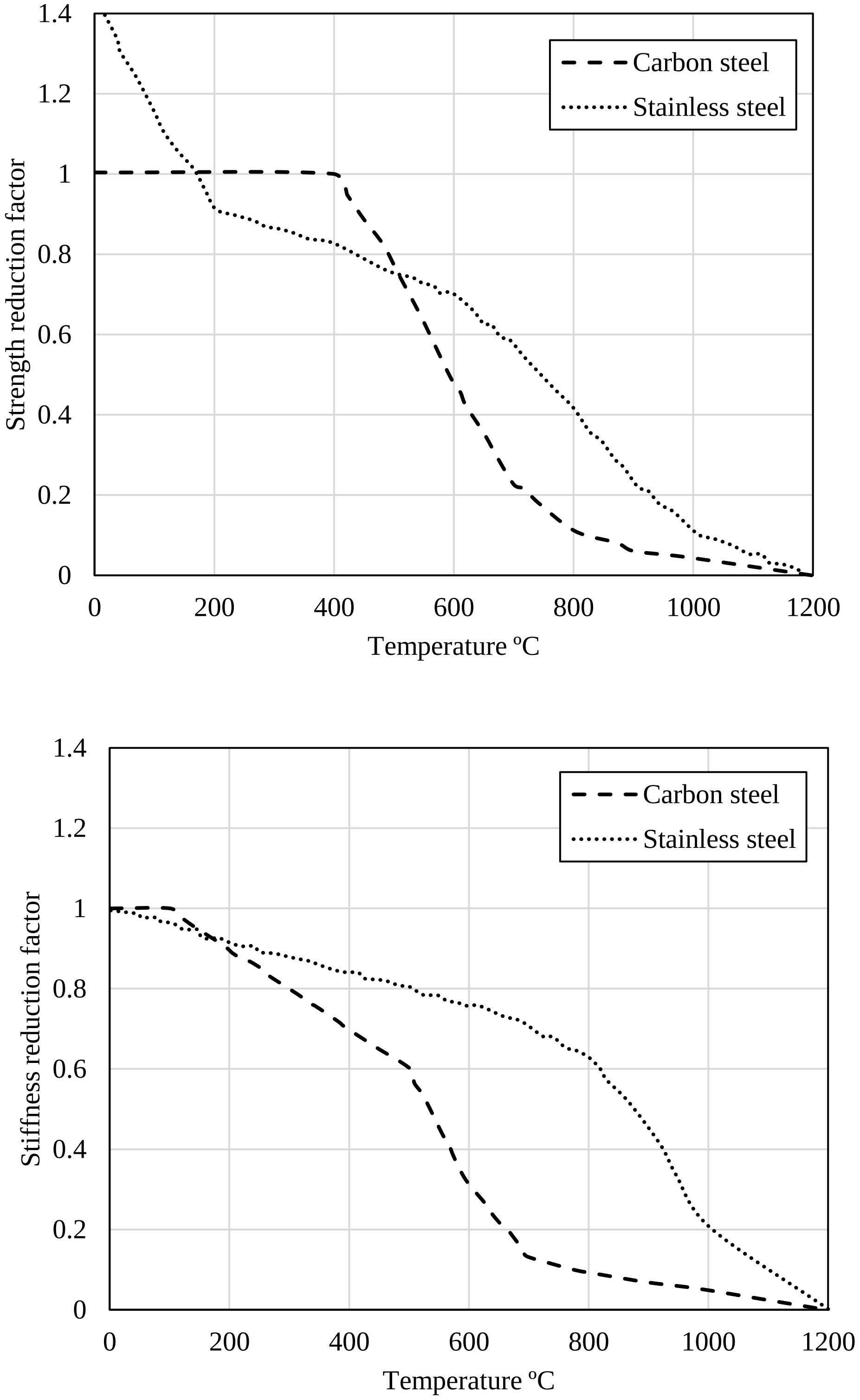
$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^{n} \qquad \text{for} \quad \sigma \leq \sigma_{0.2} \qquad (1)$$

$$\varepsilon = \varepsilon_{0.2} + \frac{\sigma - \sigma_{0.2}}{E_2} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_2}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^{m} \qquad \text{for} \quad \sigma_{0.2} < \sigma \leq \sigma_u \qquad (2)$$

In these expressions, ε and σ are the engineering strain and stress, respectively, E_2 is the tangent modulus at the 0.2% proof stress point, σ_u and ε_u are the ultimate stress and corresponding strain, respectively, $\varepsilon_{0.2}$ is the strain corresponding to $\sigma_{0.2}$ and n and m are model constants related to the strain hardening behaviour. The parameters required for applying these equations should be determined from tensile testing. Eurocode 3 Part 1-4 [90] for structural stainless steel includes guidance on appropriate values for these parameters but these may not be applicable for stainless steel reinforcement.

2.5. Properties of stainless steel reinforcement at elevated temperature

The capability of a material to retain stiffness and strength when exposed to elevated temperature is one of the most important characteristics for achieving fire-resistant structures. Stainless steel has very good strength and stiffness retention at elevated temperature owing to its distinctive constituent elements [91]. The behaviour of structural stainless steel in fire has been extensively studied in the literature (e.g. [92-95]) but there is much more limited data available on the behaviour of bare stainless steel reinforcement at elevated temperature (e.g. [85]). Moreover, there is a notable lack of any information on the behaviour of stainless steel reinforced concrete elements under fire conditions. The retention factors for the yield stress (or 0.2% proof stress) and Young's modulus for both carbon steel [96] and grade 1.4301 stainless steel [97, 90] are shown in the Fig. 5(a) and 5(b), respectively. In terms of strength, although stainless steel initially loses more strength than carbon steel, this reverses from around 400 °C and then stainless steel out-performs carbon steel quite significantly. The data for stiffness presented in Fig. 5(b) is starker, as stainless steel retains a much more significant proportion of its ambient temperature value with increasing levels of temperature exposure. These distinctive properties of stainless steel are very beneficial in the event of fire.



(a)

(b)

Fig. 5: Comparison of stainless steel and carbon steel (a) strength retention factor (b) stiffness retention factor (adapted from [97]).

As discussed previously, stainless steel has a higher coefficient of linear thermal expansion (between 14-17 × 10^{-6} /°C) compared with carbon steel (12× 10^{-6} /°C), which is an important consideration for how it bonds to the surrounding concrete during elevated temperature scenarios. Fig. 6 illustrates the variation in thermal elongation with increasing temperature for stainless steel, carbon steel and also a variety of aggregates [97]. The variation between the two metallic materials becomes greater with increasing temperature. In addition, it is evident that stainless steel does not have a phase-change plateau like occurs for carbon steel reinforcement at a temperature of around 723˚C. The figure also illustrates that there is a disparity in the thermal elongation between the concrete aggregates and stainless steel. This may not be desirable for reinforced concrete members during a fire, as the composite action between the two constituent materials may be lost, resulting in a loss of bond, greater cracking and greater levels of concrete spalling.

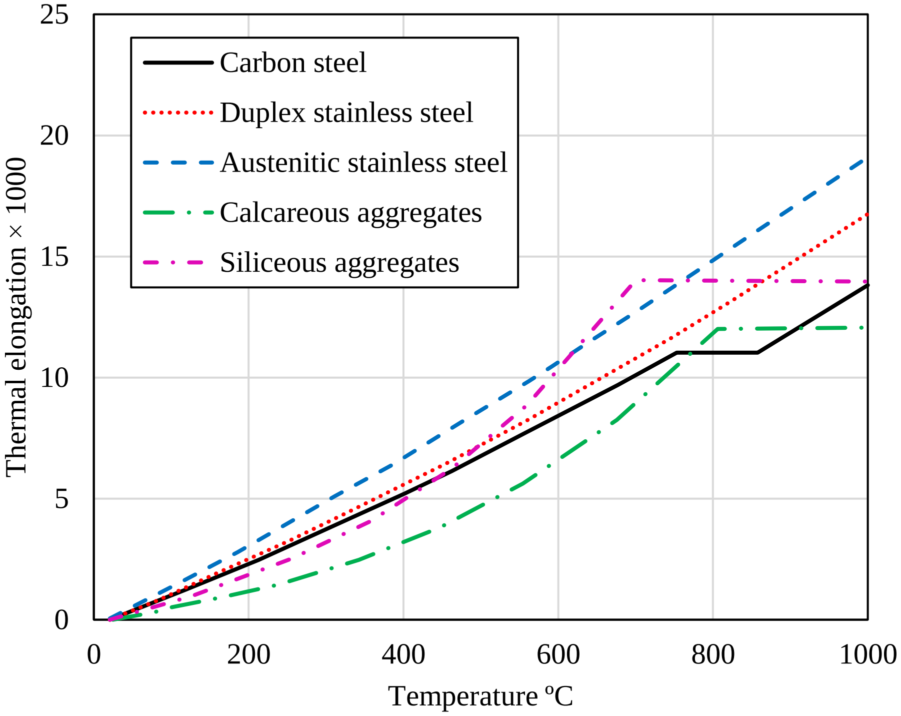


Fig. 6: Thermal expansion behaviour of austenitic and duplex stainless steels, carbon steel and aggregates (adapted from [97]).

3 Design of stainless steel RC structures

Despite the many attributes of stainless steel as a reinforcement material for concrete structures, it remains a relatively novel and under-used material for this application. As stated before, this is largely because of the common misconception about the high initial cost but is also owing to a lack of appropriate and specific design guidance. Therefore, this section highlights current design guidance as adopted in international standards for stainless steel reinforced concrete and discusses the recent developments in design methods.

3.1 Grade selection

The advantageous characteristics of stainless steel reinforcement are dependent on the constituent elements of the alloy as well as the production route, finish and product form. Therefore, it is crucial to carefully select the adequate stainless steel grade for the appropriate application. However, the availability of a wide range of stainless steel reinforcement grades may be confusing for designers and engineers who are not familiar with the subtleties of stainless steel classifications and compositions. The majority of the current international design standards do not include specific design guidance for the selection of the most suitable stainless steel reinforcement grades. The corrosion and material selection guidance given in the Annex A of Eurocode 3 Part 1-4 [90] for structural stainless steel should not be applied for stainless steel reinforcement because the passive protection cover provided by the concrete is not considered.

Both BS 6744 [72] and the American material code ASTM A955/A955M [73] adopt the strength classes and bar profiles for carbon steel reinforcement as given in EN 10080 [76] and ASTM A615/A615M [98], respectively. The stainless steel material designations in BS 6744 and ASTM A955/A955M are in accordance with those in EN 10088-1 [74] and ASTM A276 [99], respectively. Although these standards include material specifications and requirements, there is limited guidance on grade selection. The available advice on stainless steel reinforcement grade selection, which includes the version of BS 6744 [100] published in 2001 (it was removed in the 2016 updated version), BA 84/02 [62] and Markeset et al. [31], is generally governed by the service and exposure conditions of the application. The actual chloride concentration exposure levels that the alloy needs to resist are not considered. Table 5 presents the guidance notes given in BS 6744 [100] for selecting the appropriate grade of stainless steel reinforcement based on the exposure condition. This table is applicable for new construction as well as rehabilitation and restoration applications. The Design Manual for Road and Bridges [62] also has an advice note on grade selection for highways and infrastructure, as shown in Table 6. In addition, Markeset et al. [31] suggested a classification of stainless steel reinforcement grades based on the PREN (Pitting Resistance Equivalent Number) value, which is a measure of corrosion resistance, as presented in Table 7. It is also noteworthy that the reinforcement grades covered in these guidelines reflect the material that were available on the market at the time of publication, and do not incorporate newer grades (especially new duplex grades) which were introduced in more recent years.

Table 5: Guidance on the use of stainless steel reinforcement for different service conditions in the 2001 edition of BS 6944 [100].

Reinforcement grades	Service condition			
	For structures or components with either a long design life, or which are inaccessible for future maintenance	For structures or components exposed to chloride contamination with no relaxation in durability design (e.g. concrete cover, quality or water proofing treatment requirements)	Reinforcement bridging joints, or penetrating the concrete surface and also subject to chloride contamination (e.g. dowel bars or holding down bolts)	Structures subject to chloride contamination where reductions in normal durability requirements are proposed (e.g. reduced cover, concrete quality or omission of water proofing treatment)
1.4301	1	1	5	3
1.4436	2	2	1	1
1.4429	2	2	1	1
1.4462	2	2	1	1
1.4529	4	4	4	4
1.4501	4	4	4	4

Key
1 – Appropriate choice for corrosion resistance and cost.
2 – Over-specification of corrosion resistance for the application.
3 – May be suitable in some instances: specialist advice should be obtained.
4 – Grades suitable for specialist applications which should only be specified after consultation with corrosion specialists.
5 – Unsuitable for the application.

Table 6: Selection of stainless steel grades as given in BA 84/02 [62].

Exposure Condition	Stainless steel grade
Stainless steel reinforcement embedded in concrete with normal exposure to chlorides in soffits, edge beams, diaphragm walls, joints and substructures.	1.4301
As above but where additional relaxation of design for durability is required for specific reasons on a given structure or component i.e. where waterproofing integrity cannot be guaranteed over the whole life of the structure.	1.4436
Direct exposure to chlorides and chloride bearing waters for example dowel bars, holding down bolts and other components protruding from the concrete.	1.4429 1.4436
Specific structural requirements for the use of higher strength reinforcement and suitable for all exposure conditions.	1.4462 1.4429

Table 7: Classification of stainless steel reinforcement according to their corrosion resistance as proposed by Markeset et al. [31].

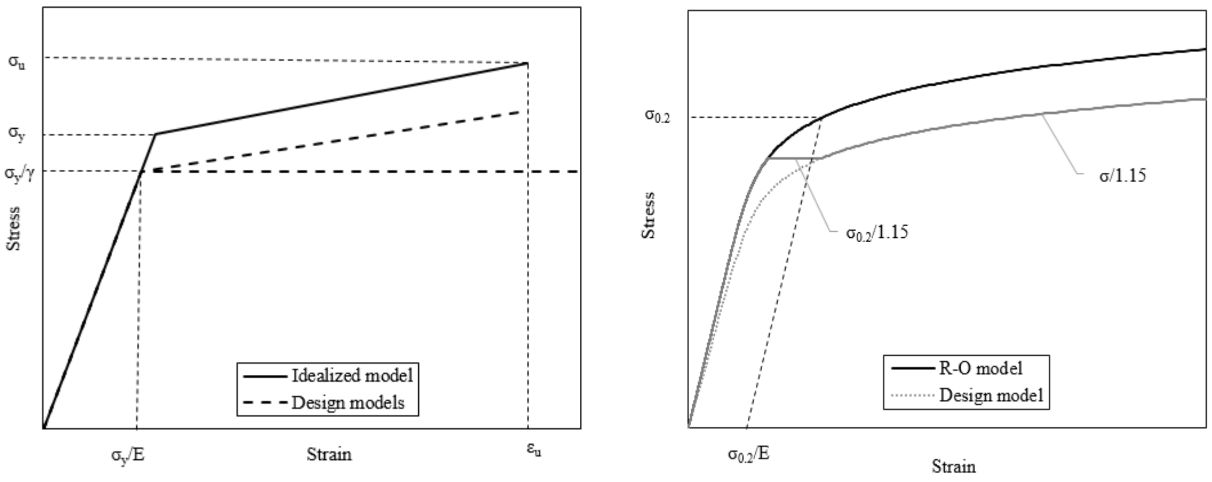
Corrosion resistance class	Steel Type	Stainless steel grade	PREN
Class 0	Carbon steel	-	-
Class 1	Austenitic stainless steel (without Mo)	1.4301	19
		1.4541	17
Class 2	Austenitic stainless steel (with Mo)	1.4401	25
		1.4429	26
		1.4436	26
		1.4571	25
Class 3	Duplex	1.4462	36

Clearly, as recognised in the design standards, different grades of stainless steel reinforcement offer various levels of corrosion resistance. Therefore, it is rational to consider that the durability requirements (e.g. the allowable design crack widths, the required concrete cover, use of reinforcement coatings or cement inhibitors during construction, etc.) for a given design may also be dependent on the grade of stainless steel reinforcement that is employed. Adopting a holistic view of the materials employed together with the required durability can lead to significant cost and material savings. Recommendations for relaxing the durability requirements have been considered by the UK Highway Agency in the Design Manual for Roads and Bridges [62]. These include allowing an increase to the allowable crack width to 0.3 mm and also a reduction of the required concrete cover to 30 mm, regardless the quality of concrete or the exposure condition. However, this does not take into account the grade employed, and it is not clear what the basis for these figures is. In addition, for highly aggressive environments, it was recommended that the minimum concrete cover of 40 mm should be maintained [7].

3.2 Structural design codes

The majority of global design standards including Eurocode 2 Part 1-1 [22] do not include explicit design rules for stainless steel reinforced concrete members. Currently, reinforced concrete design standards generally apply the design rules developed for carbon steel reinforced concrete to the design of stainless steel reinforced concrete members. This includes using an elastic-plastic stress-strain idealisation for carbon steel to represent the stainless steel material, as shown in Fig. 7(a), although this is clearly inappropriate given the different responses of carbon and stainless steel (see Fig. 4). BS 6744 [72] advises that incorporating the idealised constitutive relationship given in Eurocode 2 Part 1-1 [22] might not be appropriate for stainless steel RC design applications since the material behaviour is fundamentally different. In addition, the Technical Research Centre of Finland [101] found that designing stainless steel reinforced concrete members using the current design rules in Eurocode 2 can lead to either overly conservative or unsafe results, depending on the conditions.

Instead of the idealized bilinear material model given in Eurocode 2 Part 1-1 and presented in Fig. 7(a), BS 6744 includes a material model based on the original Ramberg-Osgood (R-O) expression previously described and given in Eq. 1. This is shown in Fig. 7(b) where the design model incorporates a partial safety factor. However, it has been shown that using the original R-O model to simulate the behaviour of stainless steel reinforcement, rather than the modified version (as given in Eq. 2, combined with Eq. 1), is not suitable as the strain hardening behaviour in the post-yield range (i.e. above the 0.2% proof stress) is overestimated [15, 23]. Moreover, neither BS 6744 nor Eurocode 2 give specific guidance on how this material model can be implemented in the design stainless steel reinforced concrete members. Given the high initial cost of stainless steel reinforcement, it is essential that more accurate design methods become available for designers and engineers, depicting the actual material response in a reliable and accurate manner.



(a) (b)

Fig. 7: Idealized design curve given in (a) Eurocode 2 Part 1-1 [22] and the British Standard [72].

3.4 The continuous strength method

The limitations outlined before in standardised design methods for structures made using stainless steel are not unique to reinforced concrete members. Previously, similar issues were identified for bare stainless steel structural elements and this led directly to the development of alternative design methods such as the continuous strength method (CSM). The CSM is a deformation-based design approach which exploits the distinctive strain hardening of stainless steel and provides more accurate load bearing capacity predictions. It is originally developed for stainless steel structural members with non-slender cross-sections [102] and then extended many times to account for different types of structural member including stainless steel-concrete composite beams [103]. More recently, it was further developed to include the design of stainless steel reinforced concrete beams [23, 24]; an overview of this approach is presented hereafter.

The new deformation-based design approach incorporates the real constitutive relationship of stainless steel reinforcement. Two different versions of the method were developed including a full analytical model accounting for the full stress-strain response of stainless steel and a simplified analytical model which considers a bilinear elastic-linear strain hardening material model; both are presented in Fig. 8. The full design method requires that the stress is identified as a function of the strain, and the inverse relationship proposed by Abdella [104] is adopted for this purpose, as given in Eqs. 3 and 4:

$$\sigma_1(\varepsilon) = \sigma_{0.2}\frac{r\left(\frac{\varepsilon}{\varepsilon_{0.2}}\right)}{1+(r-1)\left(\frac{\varepsilon}{\varepsilon_{0.2}}\right)^{p}} \qquad \text{for} \quad \varepsilon \le \varepsilon_{0.2} \qquad (3)$$

$$\sigma_2(\varepsilon) = \sigma_{0.2}\left[1+\frac{r_2\left[\frac{\varepsilon}{\varepsilon_{0.2}}-1\right]}{1+(r^{*}-1)\left(\frac{\frac{\varepsilon}{\varepsilon_{0.2}}-1}{\frac{\varepsilon_u}{\varepsilon_{0.2}}-1}\right)^{p^{*}}}\right] \qquad \text{for} \quad \varepsilon > \varepsilon_{0.2} \qquad (4)$$

where the material parameters are determined as:

$$\varepsilon_{0.2} = \frac{\sigma_{0.2}}{E} + 0.002 \qquad r = \frac{E\,\varepsilon_{0.2}}{\sigma_{0.2}}$$

$$E_2 = \frac{E}{1 + 0.002\,n/e} \qquad p = r\frac{1 - r_2}{r - 1}$$

$$e = \frac{\sigma_{0.2}}{E} \qquad m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u}$$

$$\sigma_u = \sigma_{0.2}\frac{1 - 0.0375(n - 5)}{0.2 + 185e} \qquad E_u = \frac{E_2}{1 + (r^* - 1)m}$$

$$r_2 = \frac{E_2\,\varepsilon_{0.2}}{\sigma_{0.2}} \qquad r_u = \frac{E_u(\varepsilon_u - \varepsilon_{0.2})}{\sigma_u - \sigma_{0.2}}$$

$$\varepsilon_u = \min\left(1 - \frac{\sigma_{0.2}}{\sigma_u}, A\right) \qquad p^* = r^*\frac{1 - r_u}{r^* - 1}$$

$$r^* = \frac{E_2(\varepsilon_u - \varepsilon_{0.2})}{\sigma_u - \sigma_{0.2}} \qquad n = \frac{\ln(20)}{\ln(\sigma_{0.2}/\sigma_{0.01})}$$

In these expressions, E_u is the slope of the stress-strain curve at ε_u and A is the stainless steel elongation.

For the simplified design approach, a bi-linear material model is employed to avoid the complexity of the nonlinear equations, as presented in Eqs. 5 and 6:

$$\sigma = E\varepsilon \qquad \varepsilon \le \varepsilon_y \tag{5}$$

$$\sigma = \sigma_{0.2} + E_{sh}(\varepsilon - \varepsilon_y) \qquad \varepsilon > \varepsilon_y \tag{6}$$

This approach defines the yield strain (ε_y) as the ratio between the 0.2% proof stress ($\sigma_{0.2}$) and the elastic modulus E. The slope of the strain hardening line E_{sh} is obtained using Eq. 7 as follows:

$$E_{sh} = \frac{\sigma_u - \sigma_{0.2}}{C_2\varepsilon_u - \varepsilon_y} \tag{7}$$

Following an extensive parametric study [24], it was shown that the constant C_2 should be dependent on the grade of stainless steel under consideration. Values of C_2 equal to 0.25 were recommended for beams with austenitic stainless steel grades 1.4311 and 1.4307, whereas a value of 0.3 is more suitable for beams with lean duplex stainless steel grade 1.4162.

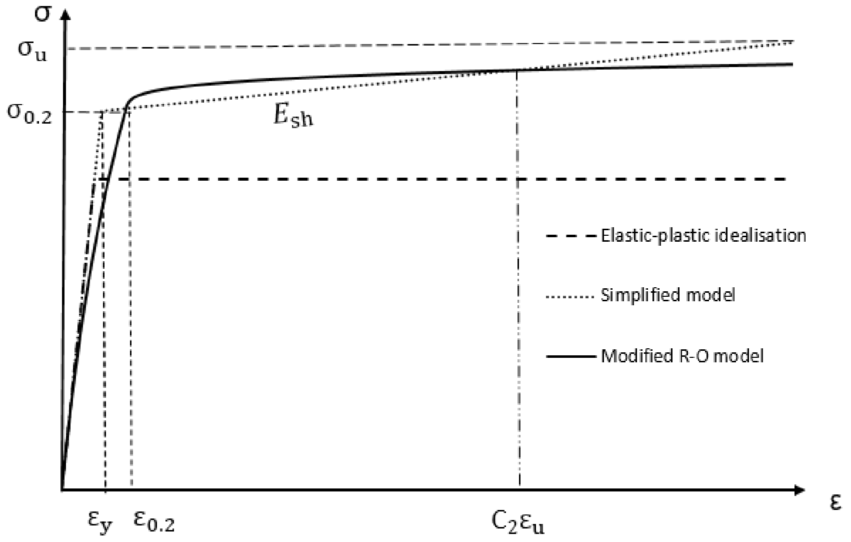


Fig. 8: The modified Ramberg-Osgood material model and the simplified version for stainless steel.

In this method, the plastic bending moment capacity of stainless steel reinforced concrete beams is calculated by applying the equations of equilibrium to the cross-sectional internal forces, which are determined based on the stainless steel material model together with the strain distribution in the section. This deformation-based design approach was thoroughly examined and validated over an extensive range of numerical and experimental data and was shown to be an effective design method that harnesses the advantageous strain hardening and ductility of stainless steel reinforcement. Moreover, it provides a more accurate, reliable and appropriate predictions of the capacity of a stainless steel reinforced concrete beam compared with current codified procedures.

3.5 Serviceability considerations

Deflections are a very important consideration in the design of reinforced concrete beams, and regularly govern the overall behaviour. An accurate depiction of the nonlinearity of the material response, and in particular the Young's modulus E, are vital in order to determine the deflections. BS 6744 [72] for stainless steel reinforcement refers to Eurocode 2 Part 1-1 [22] for the Young's modulus, and recommends that using the carbon steel E value (200 GPa) might not be appropriate for stainless steel owing to the nonlinear stress-strain curve. BS 6744 also refers to a clause in Eurocode 3 Part 1-4 [90] for structural stainless steel which requires that deflection calculations are based on an effective section with a reduced Young's modulus. However, incorporating this approach for stainless steel reinforcement without a proper validation may provide inaccurate deflection predictions causing serviceability related problems owing to the composite action between concrete and reinforcement. This issue has recently been investigated by Rabi at al. [24] through the development of an iterative analytical procedure for the determination of deflections at the mid-span of stainless steel reinforced concrete beams. This work investigated using the secant modulus and the tangent modulus of the reinforcement in the deflection calculations at the service load. The secant modulus of elasticity (E_{sec}) for stainless steel is obtained from the modified Ramberg-Osgood material model presented earlier in Eqs. 1 and 2 according to:

$$E_{sec} = \frac{E}{1+0.002\frac{E}{\sigma}\left(\frac{\sigma}{\sigma_{0.2}}\right)^{n}} \qquad \text{for} \quad \sigma \le \sigma_{0.2} \qquad (8)$$

$$E_{sec} = \frac{\sigma}{\varepsilon_{0.2} + \frac{\sigma - \sigma_{0.2}}{E_2} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_2}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^{m}} \qquad \text{for} \quad \sigma_{0.2} < \sigma \le \sigma_u \qquad (9)$$

The tangent modulus of elasticity (E_{tan}) is the derivative of the secant modulus and is determined as follows:

$$E_{tan} = \frac{\sigma_{0.2}\, E}{\sigma_{0.2} + 0.002\, n\, E\left(\frac{\sigma}{\sigma_{0.2}}\right)^{n-1}} \qquad \text{for} \quad \sigma < \sigma_{0.2} \qquad (10)$$

$$E_{tan} = \frac{1}{\frac{1}{E_2} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_2}\right)\left(\frac{m}{(\sigma_u - \sigma_{0.2})^{m}}\right)(\sigma - \sigma_{0.2})^{m-1}} \qquad \text{for} \quad \sigma_{0.2} < \sigma \le \sigma_u \qquad (11)$$

In order to obtain the secant modulus and the tangent modulus of the reinforcement at service load, the stress in the reinforcement must first be determined. An elastic analysis of the section is conducted to obtain the depth of the neutral axis (y) and the stress in the reinforcement, according to the stress and strain distributions in the section. Since the secant and tangent moduli are functions of the stress in the reinforcement, an iterative technique is required to obtain the solution. Further details of this approach are available elsewhere [24].

Based on the findings elsewhere [24], it was shown that employing the secant modulus rather than the elastic modulus in the deflection calculations results in a relatively minor improvement in the deflection predictions. On the other hand, adopting the tangent modulus in the deflection calculations provides significantly less accurate deflection predictions compared with the elastic or secant modulus. Further investigations [84] revealed similar conclusions when the secant modulus is employed at a service load corresponding to 30% of the ultimate bending moment ($0.3M_u$). However, when a service load corresponding to 67% of the ultimate bending moment ($0.67M_u$) is considered, using the secant modulus result in more accurate deflection predictions for stainless steel reinforced concrete beams. Therefore, it is recommended that the secant modulus of stainless steel is employed in deflection calculations at load levels corresponding to $0.3M_u$ and $0.67M_u$. For further simplifications to aid practicing engineers, based on the data set examined [84], a more simplified approach may be used by applying a partial modulus reduction factor of 1.0 and 0.83 to the elastic modulus in the deflection calculations at a load level corresponding to $0.3M_u$ and $0.67M_u$.

4 Recent research

In spite of the increasing usage of stainless steel reinforcement in recent years, there is still a fundamental lack of sufficient guidance and knowledge on the structural behaviour of stainless steel reinforced concrete (RC) members. This is being somewhat overcome by more research becoming available, particularly in terms of experimental, numerical and analytical investigations. This section reviews some of this work, and also provides information on how the findings need to be built upon in the future.

4.1 Structural behaviour of stainless steel reinforced concrete beams

One of the first sets of experiments on stainless steel (SS) reinforced concrete structural elements was conducted by Geromel and Mazzarella [105]. This test programme included ten conventional and high performance reinforced concrete beams with grade AISI 316L SS reinforcement. The main objective was to explore the agreement between the experimental bending moment capacity and ductility results and the corresponding theoretical values obtained on the basis of the constitutive material model available in Eurocode 2 [22] for carbon steel (CS) reinforcement. It was found that the experimental moment resistance values were 40% higher than the design values and the section ductility's were slightly lower than those calculated theoretically.

Elsewhere, Medina et al. [16] conducted experiments on two simply supported SS RC beams and two carbon steel RC beams. The SS reinforcement was grade 1.4362 duplex stainless steel. Similar to the study by Geromel and Mazzarella [105], it was shown that the SS RC beams which failed in flexure achieved greater load capacities, but slightly lower ductility's, compared with identical beams with CS rebars. On the other hand, when shear was the governing failure mode, the behaviour was very similar between the SS and CS RC beams. This is largely attributed to the relatively small cross-section of the examined specimens (which were 100 mm ×150 mm) resulting in compression failure occurring before the full strain hardening potential of the stainless steel reinforcement was exploited. Nevertheless, the ductility of the stainless steel RC cross-sections was much greater than those for the corresponding carbon steel RC beams. This is important in many applications where the development plastic hinges and a higher rotational capacity enables stresses to be redistributed through the structure during extreme events, such as an earthquake or fire. Medina et al. [16] also investigated the mechanical performance of hot-rolled and cold-rolled grade 1.4301 austenitic and grades 1.4482 and 1.4362 duplex stainless steel rebars, and compared their behaviour to that of grade B500D carbon steel reinforcement. It was shown that the elastic moduli of the stainless steel rebars was around 15% lower than that of the CS rebars. Furthermore, and as expected, the manufacturing process of the rebars had a significant effect on the strength and ductility. The cold-rolled rebars exhibited higher yield and ultimate strength compared with hot-rolled reinforcing bars, but this was accompanied by lower ultimate strains and a lower hardening ratio.

More recently, Li et al. [86] tested six simply supported RC beams to investigate the effect of the longitudinal and shear reinforcement ratios, and the type of reinforcement (CS and SS) on the flexural and shear behaviour. It was observed that the strain distribution through the depth of the beams was approximately linear in the concrete sections, verifying the validity of the common assumption that sections remain plane after deformation. Furthermore, the flexural capacity and shear capacity of SS RC beams were found to be between 32-40% greater than for the corresponding ordinary CS RC beams. Similar to the earlier findings by Medina et al. [16], when shear failure governed failure of SS RC beams, it was a brittle failure mode whilst the members that failed in flexure exhibited excellent ductility. Again, this is because the strain hardening and ductility characteristics of the SS rebars was not mobilised before shear failure occurred. It was concluded in this work that the conventional CS material constitutive model available in Eurocode 2 Part 1-1 [22] generally leads to conservative capacity predictions for SS RC members, for the range of parameters examined. This agrees with findings elsewhere [23] where the novel and innovative design method for SS RC beams described previously was developed and validated.

More recently, Rabi et al. [84] conducted an intensive experimental programme on six stainless steel RC beams and one carbon steel RC beam, for comparison. These tests were designed to investigate the effect of SS reinforcement ratios and stainless steel grade (1.4301 or 1.4436) on the flexural performance including load capacity, stiffness, cracking behaviour, as well as the deflection levels at the service load. It was shown that for beams with identical geometries, boundary conditions and reinforcement ratio, the flexural capacity of those with stainless steel rebars was consistently greater than for those with carbon steel reinforcement. Moreover, all of the SS RC beams exhibited enhanced ductility and greater deflection capacity before failure occurred. It was concluded that current available design guidance, which generally adopt an elastic-plastic material model for the reinforcing steel, underestimate the moment capacity of SS RC beams while the design method proposed by Rabi et al. [23] provided better and more accurate predictions.

4.2 Behaviour of stainless steel RC Columns

There has been very little experimental or numerical analysis into the behaviour of RC columns with stainless steel reinforcement, with only two sources available in the literature. Khalifa [106] conducted an experimental, numerical and analytical investigations into the behaviour of SS RC columns subjected to eccentric compressive loading. It was observed that as the reinforcement ratio increased, the flexural stiffness and the load capacity of the columns also increased but their ductility decreased. This study proposed a method to determine an equivalent stress to represent the yield strength (or the 0.2% proof strength) for duplex and austenitic SS rebars which is then employed to calculate the flexural capacity. Building on this work, Li et al. [107] examined the behaviour of eight SS RC columns and one CS RC column, for comparison, under different loading eccentricities and reinforcement ratios. It was shown that the location of the load application, relative to the centroid of the section, had a strong influence on the structural behaviour of SS RC columns in terms of the distribution and propagation of cracks, the ultimate load capacity and also the level of ductility which can develop due to combined effects of compressive axial loading as well as the bending stresses induced through the eccentric loading. It was shown that the failure modes for SS RC columns subjected to eccentric loading were similar to those reinforced with CS bars. A theoretical model was proposed to predict the compressive load-bending moment interaction curve for SS RC columns based on the numerical and experimental data.

4.3 Cyclic behaviour of stainless steel RC members

Stainless steel is a very ductile material, as stated before, and thus provides an excellent option for cyclic loading applications where its ability to survive even after large levels of deformation can be exploited. These applications include both low cycle fatigue scenarios, such as earthquakes, as well as high-cycle fatigue scenarios. Nevertheless, as stainless steel is still a relatively novel structural material especially in RC members, there has been limited research into the behaviour under cyclic loading, and the research that does exist has been quite recent. For example, Zhang et al. [108] tested five RC slabs which were reinforced with either grade 1.4362 duplex SS or carbon steel rebars, and subjected to cyclic fatigue loading. It was shown that the SS reinforced concrete slabs had significantly better fatigue performance compared with carbon steel reinforced concrete slabs, including lower deflections, steel strains and crack widths as well as longer fatigue life. It was also shown that the fatigue performance of SS RC slabs can be further improved by increasing the reinforcement ratio, although an optimal value for the reinforcement ratio was not presented.

Melo et al. [109] investigated the response of RC columns reinforced with either carbon steel rebars or grade 1.4462 duplex stainless steel and subjected to combined axial compressive load as well as cyclic lateral loading conditions, thus simulating an earthquake. It was shown that the seismic behavior of both the CS and SS columns were similar to each other until the maximum capacity was reached. Beyond this, the CS RC column exhibited more softening compared to the SS RC column. Furthermore, the SS RC column dissipated about 56% more energy before the ultimate point was reached compared with the CS RC column because it was able to reach greater ultimate drifts without failure. It was observed that the longitudinal rebars buckled during the cyclic loading test. Therefore a series of material tests were conducted on grade 1.4301 austenitic and grade 1.4362 duplex stainless steel rebars under cyclic loading [110]. Based on the results, a new compressive stress-strain model that considered the effect of inelastic buckling was proposed. Zhang et al. [83] investigated the seismic behaviour of stainless steel reinforced concrete columns and found that the SS RC columns exhibited good ductility. An increase in the shear reinforcement ratio enhanced the seismic performance, although limiting values for this effect were not provided, while an increase in the applied axial compressive load reduced the ultimate strength capacity and deflection.

Most recently, Xu et al. [80] investigated the seismic performance of RC beam-column edge joints with austenitic stainless steel reinforcement. The SS RC edge frame joints exhibited greater load bearing capacity and cracking loads compared with identical joints made using carbon steel rebars as well as improved ductility, deflection capacity and levels of energy dissipation. The overall behaviour patterns in terms of shear and bending failure were very similar for the members reinforced with either SS or CS rebars.

4.4 Bond behaviour of SS embedded in concrete

The bond strength that develops between the reinforcing bars and the surrounding concrete is an important phenomenon for the structural performance of RC members. Good bond strength is important for controlling cracking, and maintaining the composite behaviour of the two constituent materials. On the other hand, it also plays a role in the overall ductility of the section, especially during extreme loading events such as a fire or earthquake, when high levels of bond can lead to stress concentrations in the reinforcement. In this context, having an accurate measure of the level of bond that develops is very important, as is ensuring that suitable bond models are available in design. Even for carbon steel RC, there are different approaches to dealing with bond in various codes, and there is very little specific information in the codes for SS RC.

In recent years, Rabi et al. [21] conducted an extensive experimental programme to investigate the bond behaviour for different arrangements of SS rebar embedded in concrete. The test programme studied the bond-slip relationship for both austenitic SS and CS rebars embedded in different types of concrete using pull-out testing. It was shown that SS rebars developed approximately 28% lower bond strength compared with CS rebars on average, as well as lower residual bond values and a steeper softening branch of the bond stress-slip curve. Nevertheless, the design standards such as Eurocode 2 Part 1-1 [22] and Model Code 2010 [111] were shown to provide very conservative predictions for the bond strength, anchorage and lap lengths compared to those calculated based on the experimental results. Therefore, it was concluded that although current design rules which were developed for CS RC can be safely applied for SS RC members, there is significant scope for improvement of the design rules by developing specific procedures for SS RC.

Accordingly, a new bond stress-slip model for splitting and pull-out failure was developed, based on a similar format to the existing Model Code 2010 method [111], for both CS and SS rebars embedded in concrete. The bond-slip response proposed by Model Code 2010 for splitting failure underestimated the experimental response while the new bond-slip curves for stainless and carbon steels were more in line with the experimental results. Implementing the proposed curves improves the average ultimate bond strength design values for stainless and carbon steel rebars by 22% and 38%, respectively. Additionally, the Model Code 2010 bond model for pull-out failure resulted in lower ultimate bond strength, a softer response in the ascending and descending branches and higher residual bond strength, compared to the experimental results. The new proposed model identified more accurate parameters in the bond-slip model that provide excellent agreements with experimental response especially in the post-peak range.

More recently, Li et al. [79] tested grade 1.4362 duplex SS embedded in concrete with different cover distances and concrete strengths. Similar to Rabi et al. [21], the observed failure modes were either pull-out or splitting failure. The type of failure depended on the diameter of the reinforcement, the level of concrete cover provided as well as the tensile strength of the concrete. It was concluded that if the ratio of the concrete cover to the bar diameter was less than 4.5, combined with a relatively low concrete tensile strength, failure was by concrete splitting; otherwise, failure occurred by pull-out of the rebar and there was generally a greater bond strength developed.

Aldaca et al. [112] also conducted a series of pullout tests on SS and CS bars encased in concrete, although in this case, the specimens were submerged in sea water. The samples were left in seawater with 3.5% content chloride and exposed to simulated tidal marine environments. The results of the bond tests showed that the maximum bond strength for the stainless steel reinforcement was significantly greater than that of the carbon steel rebars following exposure to the harsh marine environment. Further experimental and analytical studies were conducted by Pauletta et al. [113] to investigate the bond behaviour of both austenitic and duplex stainless steel RC with different concrete cover thicknesses and strength values, and rebars diameters. Three different types of failure were observed including concrete tensile failure, pull-out failure, and splitting failure. The specimens with concrete tensile failure had low bond strength and slip while those which failed by pull-out achieved higher bond and slip values, as well as more ductile behaviour. It was concluded in this work that for the range of bars and parameters examined, the bond behaviour of SS and CS rebars are quite similar to each other, in contrast to the findings of others. This may be owing to the surface characteristics of the SS rebars.

Finally, Freitas et al. [114] investigated the bond characteristics of SS rebars embedded in low binder concrete (LBC), to achieve more sustainable construction. In this case, the compactness of the concrete mixture was the main parameter controlling the bond development. It was observed that the specimens with SS rebars embedded in the LBC exhibited greater bond strength in comparison to those with traditional concrete. It was concluded that LBC with reduced cement content of up to one quarter of the minimum recommended in EN 206-1 [115] can be used safely with SS reinforcing bars.

5 Conclusions and recommendations for future research

This paper presents a thorough review of the existing knowledge on stainless steel reinforced concrete, as a realistic and attractive structural solution. The material properties, as well as existing design methods and obtained performance data were presented, discussed and reviewed. From these discussions, it is clear that the engineering research community have acknowledged and embraced the great advantages that stainless steel reinforced concrete can offer the construction sector compared with traditional materials, especially when a long maintenance-free life cycle is required. Corrosion of steel reinforcement leads directly to many structural problems including a reduction in the load-bearing capacity of RC members, deterioration of the bond behaviour between rebar and concrete, and spalling of concrete cover. In addition, there are many secondary problems and challenges, such as the inspection and maintenance regime required for deteriorating structures, requirements to close key infrastructure, and the costs associated with rehabilitation. In this context, stainless steel reinforcement provides an alternative to traditional carbon steel reinforcement owing to its outstanding material and structural behaviour. However, it comes at a high initial cost compared with carbon steel, and also there is a lack of efficient design guidance, as well as long-term cost data.

The key areas that still require significant research focus include, but are not limited to, the following topics: (i) fatigue behaviour of SS RC, which is very important for bridge applications, (ii) fire behaviour, which is relevant for building and bridge structures, as well as tunnel linings, (iii) creep behaviour, to understand the long term performance, (iv) the use of SS in pre-cast and pre-stressed concrete, as there is no information on this in the public domain, (v) the structural behaviour of whole systems of SS RC, including members and connections under combined loading scenarios, and (vi) structural analysis, including the distribution and redistribution of moments and rotations in indeterminate structures. One other key area which needs urgent attention is the whole-life costs, including environments costs, of using SS RC in construction. It is intuitive that using maintenance-free, corrosion-resistant materials in place of less high-performing materials provides greater long-term benefits, but these benefits need to be quantified and better understood, as well as compared with other novel materials such as FRP reinforcement, shape-memory alloys, etc.

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