ANALYSIS OF CONCRETE BEAMS REINFORCED WITH STAINLESS STEEL

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Abstract

Stainless steel has been exploited widely in the construction industry and is used in a range of applications owing to its characteristics in terms of corrosion resistance, long life cycle, formability, durability and recyclability. The stress-strain behaviour of stainless steel is different from that of carbon steel. Carbon steel demonstrates linear-elastic behaviour with a clear yield point followed by plastic deformation with little strain hardening. On the other hand, stainless steel exhibits a more nonlinear yet continuous stress-strain response without a clearly defined yield point. Currently, the vast majority of global design standards, such as Eurocode 2, do not fully exploit the ductility and strain hardening characteristics of stainless steel in the plastic design of reinforced concrete structures. This assumption leads to very conservative capacity predictions since stainless steel exhibits a high degree of strain hardening. Therefore, the aim of this paper is to study the design of stainless steel reinforced concrete beams, and to investigate the impact that neglecting strain hardening has on the load-bearing capacity. Towards this end, a finite element model has been developed and validated using experimental data available in the literature and is described herein. Then, the model is used to investigate the behaviour of concrete beams with stainless steel reinforcement and to study the influence of the most salient parameters.

Keywords: stainless steel rebar, concrete beam, finite element analysis.

1. Introduction

Stainless steel is exploited widely in the construction industry and can be found in a wide range of applications owing to its favourable characteristics in terms of corrosion resistance, long life cycle, formability, durability and recyclability. Stainless steel was first introduced in the UK by Brearley in 1912 who referred to it as ‘rustless steel’ (Truman, 1985). By definition, stainless steels are a group of corrosion resistance alloying steels who possess a minimum chromium content of 10.5% and a maximum carbon content of 1.2%. Traditionally, it has typically been employed in environments where corrosion resistance is required. There are five main categories of stainless steel, and each grade is classified according to its metallurgical structure: (1) austenitic, (2) ferritic, (3) duplex, (4) martensitic and (5) precipitation hardened stainless steel (BS EN 10088-1, 1995). Austenitic and duplex stainless steels are the most common for structural applications including reinforced concrete structures. Austenitic stainless steels contain 17-18% chromium whilst the duplex grades contain 22-23% chromium. Both families provide excellent strength and corrosion resistance, and have slightly varying other characteristics, which can be exploited depending on the application.

This paper is concerned with the behaviour of stainless steel reinforced concrete structures. In that context, stainless steel reinforcement can provide an ideal solution for concrete members where deterioration and corrosion is expected to occur, such as bridges, tunnels and other structures exposed to harsh environments. It can also be efficiently used for the restoration and rehabilitation of existing concrete structures (Pérez-Quiroz et al., 2008). In spite of the high initial cost of stainless steels, they can still provide a competitive and efficient solution over the life-cycle of a structures and reduce or even eliminate the need for costly monitoring and maintenance.

Stainless steel reinforcement is currently available in the open market in a number of different grades including austenitic grades 1.4311, 1.4307 and 1.4301 and duplex grades 1.4462, 1.4162 and 1.4362. Grade 1.4307 is the most commonly found grade used in construction and is a standard low-carbon austenitic stainless steel whereas grade 1.4311 is also a low-carbon austenitic stainless steel but with improved low-temperature toughness and strength owing to its higher nickel and nitrogen content. Both of these grades are very suitable for low magnetic structural applications. Grade 1.4362 is a duplex stainless steel which offers superior corrosion resistance due to the relatively high nickel content compared to the austenitic grades. In recent years, a new type of duplex stainless steel has been developed which has a relatively low nickel content and these are known as the lean duplex grades. Grade 1.4162 is in this category and offers excellent corrosion resistance whilst also possessing around double the characteristic strength of austenitic stainless steel for almost the same cost, owing to the low nickel content.

In addition to strength and corrosion resistance, one of the great advantages of stainless steel compared with carbon steel is the greater ductility and strain hardening capacity. Currently, the vast majority of global design standards, including Eurocode 2, do not include an efficient design model for concrete structures with stainless steel reinforcement as they do not fully exploit the ductility and strain hardening characteristics of stainless steel. Although this assumption is acceptable for carbon steel reinforced concrete (RC), it gives very conservative predictions when stainless steel reinforcement is employed. There has been considerable research in recent years into the mechanical properties of stainless steel reinforcement (e.g. Alvarez Bautista & Velasco (2011), Serdar, Žulj & Bjegović, (2013) & Bautista et al. (2007)), although the vast majority of the research has focussed on the behaviour of the bare stainless steel bar and its corrosion resistance. Therefore, the aim of the current paper is to assess the behaviour and design of stainless steel reinforced concrete beams and to investigate the impact of neglecting strain hardening in the design roles given in Eurocode 2 on the load-bearing capacity. Accordingly, a finite element model has been developed using the ABAQUS software (Dassault Systèmes, 2016) and validated using available experimental data in the literature. The finite element model is then used to investigate the behaviour of concrete beam with stainless steel and to determine the influence of several important parameters such as concrete strength and reinforcement grade.

2. Stainless steel material properties

The stress-strain behaviour of stainless steel is different from that of carbon steel, in that carbon steel has a linear elastic response with a clear yield point, which is then followed by a moderate degree of strain hardening. On the other hand, stainless steel exhibits a predominantly nonlinear response with an undefined yield point and significant strain hardening. In the absence of the clearly defined yield point, the 0.2% proof stress is typically used for stainless steel to define the yield point. Cold worked carbon steel reinforcement has similar behaviour to stainless steel in terms of the shape of the stress-strain curve, but exhibits significantly less strain hardening and also a much lower ultimate strain. The most commonly used material model in Eurocode 2 is an elastic-perfectly plastic stress-strain relationship for representing the reinforcement, although there is the option of considering an inclined top branch to capture some strain hardening in the response. However, for this approach, there is a requirement to check the strain limit and the ultimate strength. The elastic-perfectly plastic relationship is widely used in design and therefore it is selected herein for the comparison. Although this is a valid assumption for structures reinforced with carbon steel, it leads to an overly conservative prediction of the section capacity when stainless steel rebar is employed. For this reason, in the current work the relationships proposed by Ramberg-Osgood (1943) and updated by Mirambell & Real (2000) and Rasmussen (2003), are employed to represent the stress-strain relationship of stainless steel, as presented in equations (1 and 2) and known hereafter as the modified Ramberg-Osgood material model:

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

$$\varepsilon = \varepsilon_{0.2} + \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_2}\right) \qquad \sigma > \sigma_{0.2} \tag{2}$$

In these expressions, ε and σ are the engineering strain and stress, respectively, m and n are model constants related to the strain hardening, E is the Young's modulus, $\varepsilon_{0.2}$ and $E_{0.2}$ are the strain and initial tangent modulus corresponding to the 0.2% proof stress and σ_u and ε_u are the ultimate stress and strain, respectively.

In order to build a greater understanding of the stress-strain characteristics of stainless steel reinforcement and to evaluate the deficiencies in current design rules, the experimental data presented in the literature (Gardner et al., 2016) is compared to the relationships obtained using the material model presented in equations (1 and 2), as well as the elastic-plastic material model currently provided in Eurocode 2. A number of different grades of austenitic and lean duplex stainless steel are considered, including grades 1.4162, 1. 4307 and 1.4311. Figure 1 presents the experimental stress-strain curves for stainless steel reinforcement tested by Gardner et al. (2016). The previously-discussed nonlinear relationship is clear, with no defined yield point and a high degree of strain hardening. All of the tested grades exhibited excellent strength and ductility.

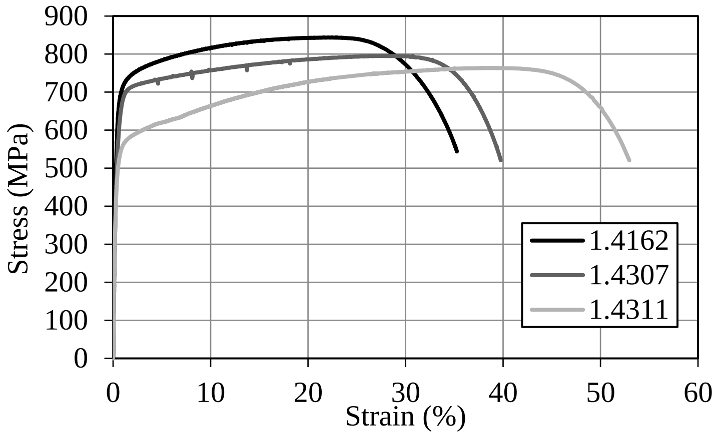

Figure 1. Stress-strain curves for different grades of stainless steel (Gardner et al., 2016).

Error! Reference source not found.-4 present the same experimental stress-strain curves as presented in Figure. 1 (Gardner et al., 2016), together with the relationships obtained using the modified Ramberg-Osgood material model and Eurocode 2, for grade 1.4162, grade 1.4307 and 1.4311, respectively. In these figures, both the overall response is presented as well as a closer view of the elastic portion of the behaviour. The parameters for these stress-strain curves are presented in Table 1. Generally, it is shown that the modified Ramberg-Osgood model provides a better representation of the experimental behaviour for all stainless steel grades compared with Eurocode 2. Clearly, ignoring strain hardening in the material response leads to significant errors in the stress-strain curve. The modified Ramberg-Osgood (RO) model provides an excellent depiction of stainless steel grade 1.4311, however it slightly overestimates the stresses for lean duplex grade 1.4162, and slightly underestimates the response of austenitic stainless steel grade 1.4307. The material details of these grades are summarized in Table 1.

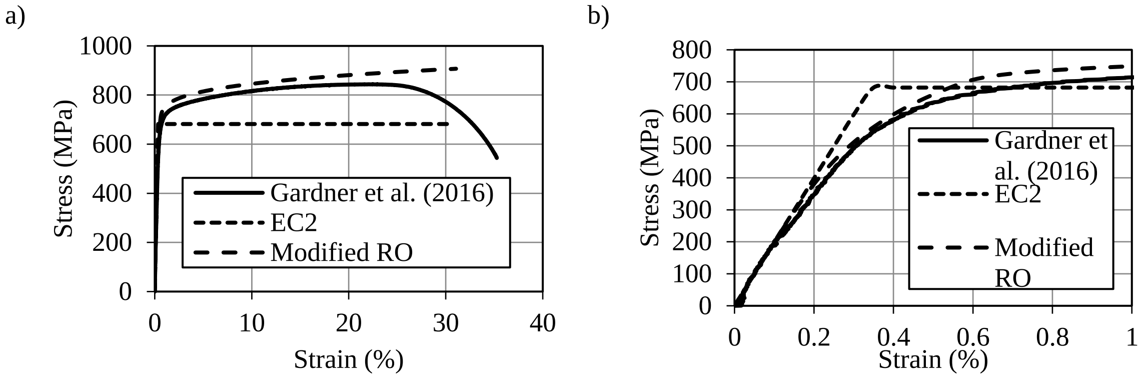

Figure 2. Experimental and design stress-strain curves for grade 1.4162 (a) full curve and (b) more detailed view of the elastic region.

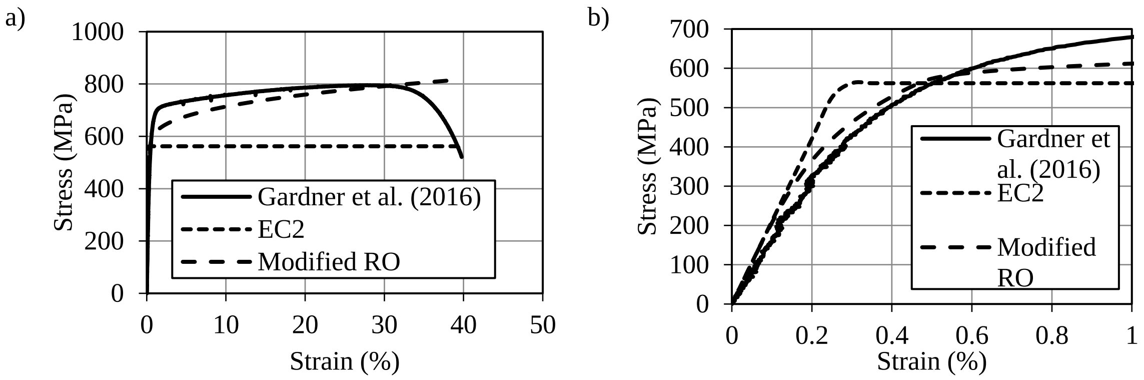

Figure 3. Experimental and design stress-strain curves for grade 1.4307 (a) full curve and (b) more detailed view of the elastic region.

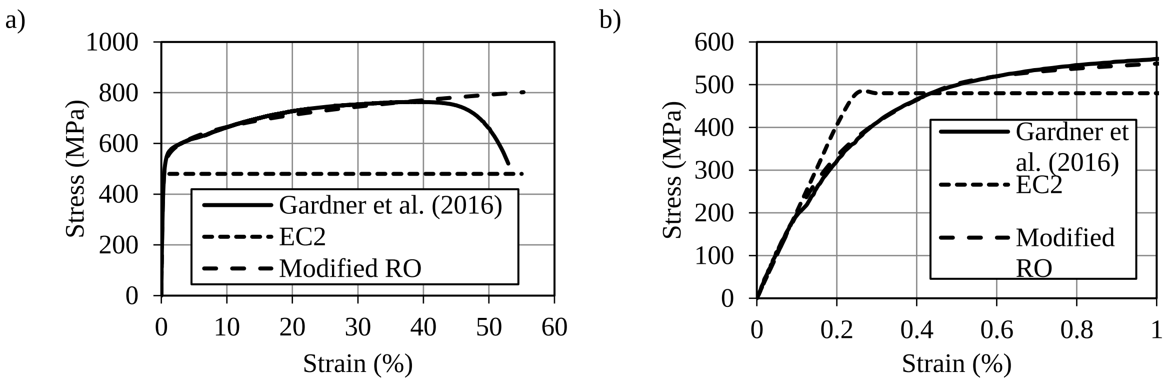

Figure 4. Experimental and design stress-strain curves for grade 1.4311 (a) full curve and (b) more detailed view of the elastic region.

Table 1: Material properties of stainless steel (Gardner et al., 2016).

Stainless steel type	**Grade**	**Bar diameter** (mm)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	E (MPa)	ε_u (%)	n	m
Austenitic	1.4311 (304LN)	12	480	764	202600	38.6	4.7	4.8
Lean duplex	1. 4162 (LDX2101)	12	682	874	199100	20.4	5.3	5.0
Austenitic	1.4307 (304L)	12	562	796	210200	30.7	4.7	4.8

3. Finite element model

In order to understand the behaviour of stainless steel reinforced concrete beams, a finite element model has been developed using the ABAQUS software and validated using experimental data available in the literature. The concrete beam is modelled using 3D, eight-noded hexahedral solid elements (C3D8 in the ABAQUS library), and the stainless steel reinforcement is modelled using beam elements (B31). In order to avoid localized stresses at the support and also at the loading point, the forces are distributed across a 3 cm surface. Loading is applied to the beam in displacement control through two point loads. The boundary conditions are designed to simulate a pinned connection and therefore the beam ends are restrained against vertical displacements but allow movement at the other degrees of freedom. It is only necessary to model a quarter of the beam due to symmetry, which reduced the computational time and cost.

A number of concrete material models are provided in the ABAQUS software including the smeared crack concrete model and concrete damage plasticity (CDP) model. The CDP model is selected in this study for simulating the concrete behaviour as it is suitable for applications where the concrete is subjected to static loads. The CDP model is based on continuum damage mechanics and considers two failure modes, namely cracking of the concrete in tension and crushing in compression. The material behaviour is defined in terms of the elastic, plastic, compressive and tensile properties. For the compression behaviour, the model given in Eurocode 2 (CEN, 1992) is adopted, given as:

$$\sigma_c = (\frac{k\eta - \eta^2}{1 + (k-2)\eta}) f_{cm} \tag{3}$$

where

$$k = 1.05 E_{cm} \frac{\varepsilon_{c1}}{f_{cm}} \tag{4}$$

$$k = 1.05 E_{cm} \frac{\varepsilon_{c1}}{f_{cm}} \tag{5}$$

$$\eta = \frac{\varepsilon_c}{\varepsilon_{cu1}} \tag{6}$$

$$\varepsilon_{c1}(\%) = 0.7 (f_{cm})^{0.31} \leq 2.8 \tag{7}$$

$$E_{cm} = 22(0.1 f_{cm})^{0.3} \tag{8}$$

In these expressions, σ_c is the concrete compressive stress; f_{cm} and f_{ck} are the mean value of concrete cylinder compressive strength and the characteristic cylinder strength, respectively; ε_{c1} is the strain at the peak stress of concrete while ε_{cu1} is the ultimate strain of concrete which equals to 0.0035 as suggested by Eurocode 2; and E_{cm} is the Young's modulus of concrete.

The tensile behaviour of the concrete is modelled using a linear relationship up to the ultimate tensile stress (f_t) followed by gradually decreasing tensile stress with increasing tensile strain using the power stress-strain relationship proposed by Wang & Hsu (2001), which inherently incorporates the effects of tension stiffening. The effect of the bond between the rebar and the concrete is approximated within this tension stiffening branch. This relationship, which presented in , provides an accurate post-failure response in tension compared to linear or bi-linear relationships, and it has also been successfully used by other researchers for similar studies (e.g. Kmiecik & Kamiński, 2011; Dede & Ayvaz, 2009).

$$\begin{aligned} \sigma_t &= E\varepsilon_t & \varepsilon_t &\leq \varepsilon_{cr} \\ \sigma_t &= f_t(\frac{\varepsilon_{cr}}{\varepsilon_t})^{0.4} & \varepsilon_t &> \varepsilon_{cr} \end{aligned} \tag{9}$$

where ε_t is the concrete tensile strain corresponding to the tensile stress (σ_t) and ε_{cr} are the tensile cracking strain corresponding to f_t.

The stainless steel material is modelled using elastic-perfectly plastic relationship in Eurocode 2 and also using the modified RO model given in equations (1 and 2).

4. Validation of the finite element model

4.1. Experimental tests

The FE model is validated using three reinforced concrete beams from different experimental programmes. The geometric details for these beams, namely U2, O and SS, can be found in Alfano et al. (2011), Obaidat et al. (2011) and Alih & Khelil (2012), respectively. Of these experiments, only beam SS used stainless steel rebar, which was austenitic grade 1.4311 with 20 mm bar diameter, while the other beams were reinforced with traditional carbon steel. All of the beams were tested under a four-point bending arrangement with the loads being applied under displacement control. Beam U2 was loaded until cracking occurred and then unloaded to zero before being reloaded up to failure, while beam SS was loaded up to 80 kN where the test was stopped, most likely due to the capacity of the test arrangements being reached. On the other hand, beam O was loaded monotonically until failure occurred.

4.2. Load-displacement response

Figure 5 presents the load-displacement curves for beams U2, O and SS obtained experimentally and numerically. It is observed that the FE model provides an excellent depiction of the experimental response in all cases in terms of initial stiffness, cracking point and ultimate load. The slight discrepancies that exist for the initial stiffness is due to some localised cracking in the experiment which is not being captured by the FE model. Nevertheless, it is concluded that there is a good agreement between the numerical load-displacement response and the corresponding experimental results for the all of the beams, thus validating the FE model.

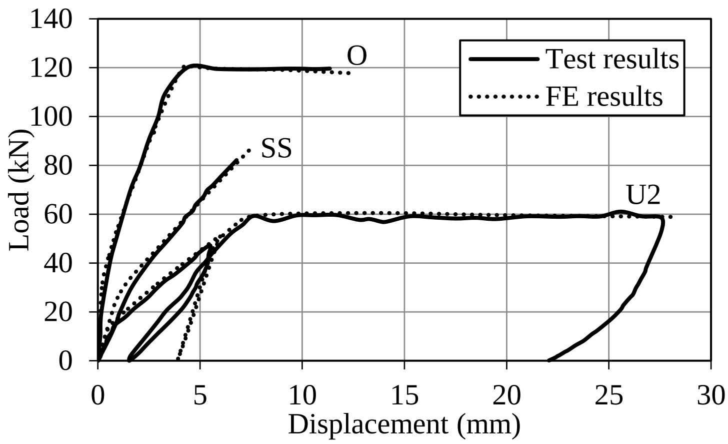

Figure 5. Comparison between the experimental and numerical load-displacement curves for beams U2, O and SS.

5. Stainless steel reinforced concrete beams

In this section, the validated FE model described in the previous sections is utilized to investigate the effect of neglecting strain hardening on the load-bearing capacity of concrete beams with stainless steel reinforcement by implementing the elastic-perfectly plastic material model provided currently in Eurocode 2 as well as the modified RO model which captures the strain hardening contribution. Beam SS is utilised herein for illustrative purposes as it is the only beam of those discussed in previous sections for validation which was reinforced with stainless steel. Then, the validated model is utilized to conduct a parametric study focussing on the influence of stainless steel grade and concrete strength on the overall behaviour.

Figure 6 presents the load-displacement curves obtained using both material models in the FE simulation. It can be clearly observed that there is an excellent agreement in all cases in terms of the initial stiffness and the cracking point, regardless of the model used for the stainless steel rebar.

However, later in the response, there is a considerable difference in terms of the plastic behaviour as the simulation which employed the modified RO model exhibits significant strain hardening, whilst the response generated using the elastic-perfectly plastic material model from Eurocode 2 has a well-defined yield point followed by no strain hardening. The effect of including strain hardening in the analysis is clearly demonstrated by the significant difference in the ultimate loads. The beams reinforced with stainless steel grades 1.4311, 1.4162 and 1.4307 and depicted using the modified RO material model have load capacities which are 48.6, 24 and 37.17% greater than those modelled with the material model in Eurocode 2, respectively. These results emphasize the deficiency of the design rules in Eurocode 2 for concrete beams with stainless steel mainly because of neglecting the significant strain hardening characteristic.

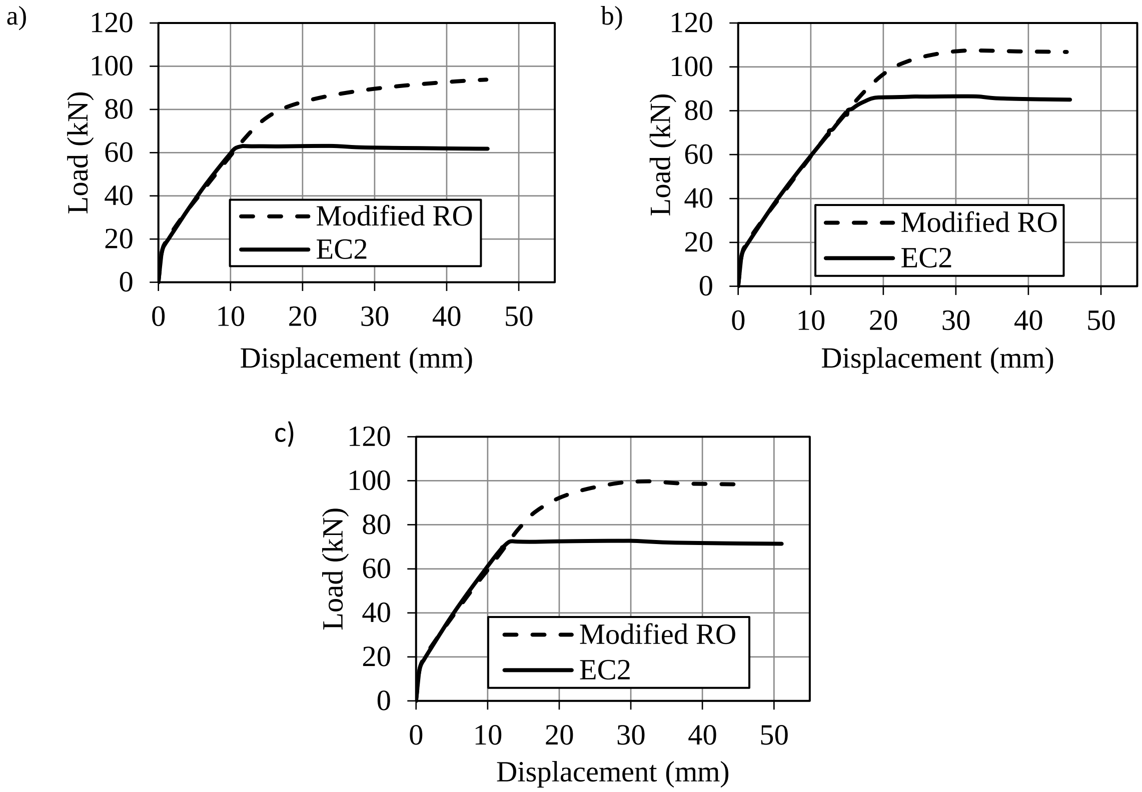

Figure 6. Influence of the stainless steel material model on the load-displacement response for beams reinforced with (a) grade 1.4311, (b) grade 1.4162 and (c) grade 1.4307 stainless steel.

Table 2 presents a comparison of the ultimate loads obtained numerically using either the reinforcement material model in Eurocode 2 or the modified RO material model for different grades of stainless steel and a range of concrete strengths. For all cases, the beams modelled in accordance with the modified RO model have an average of a 33% greater ultimate load capacity compared with those modelled using the Eurocode 2 approach. Moreover, using higher concrete strength results in further exploitation of the strain hardening as illustrated in the final column in Table 2, owing to the delay in the onset of concrete crushing. These results emphasise that the design rules suggested by Eurocode 2 provide overly-conservative results and underestimate the capacity of the concrete beams reinforced with stainless steel.

Table 2. Comparison between the ultimate load capacity obtained numerically by implementing Eurocode 2 and Rasmussen reinforcement material models.

Stainless steel grades	**Concrete grades**	**Ultimate load using Eurocode 2 material model** (kN)	**Ultimate load using Modified RO material model** (kN)	**Modified RO / Eurocode 2** (%)
1.4311	30	59.58	78.9	+32.4

	40	62.16	91.37	+47
	50	63.05	93.7	+48.6
1.4162	30	84.93	101.45	+19.45
	40	86.33	104.88	+21.49
	50	86.57	107.37	+24
1.4307	30	71.21	94.14	+32.2
	40	71.93	97.13	+35
	50	72.7	99.72	+37.17

6. Conclusions

Stainless steel material is a very ductile material that exhibits significant levels of strain hardening. Most design rules (such as Eurocode 2) do not provide specific guidance for stainless steel reinforced concrete members and thus neglect this distinctive feature in the design. In the current study, a finite element model has been developed and validated using the available experimental data in the literature in order to investigate the effect of neglecting the strain hardening on the behaviour stainless steel concrete beams. It is concluded that ignoring strain hardening of stainless steel results in overly-conservative capacity predictions and underestimates the load-bearing capacity of the concrete beams with stainless steel. It is acknowledged that this is a simplistic analysis, which does not consider the influence of important parameters such as the bond strength, but nevertheless, the inadequacies of current design methods are highlighted and the need for greater research in this area is clear.

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