Case Studies in Construction Materials 20 (2024) e03013

Contents lists available at ScienceDirect

Case Studies in Construction Materials

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

Description of the constitutive behaviour of stainless steel reinforcement

Musab Rabi [a], Rabee Shamass [b], K.A. Cashell [c,*]

[a] Dept of Civil Engineering, Jerash University, Jordan
[b] Department of Civil and Environmental Engineering Brunel University London, London, UK
[c] Department of Civil Environmental and Geomatic Engineering, University College London, UK

ARTICLE INFO

Keywords:
Stainless steel reinforcement
Stress-strain material model
Tensile tests
Eurocode 2
Eurocode 3

ABSTRACT

This paper presents a comprehensive analysis of the constitutive relationship of stainless steel reinforcement and proposes new material models for both austenitic and duplex stainless steel bars. These are an advancement on existing models which have largely been developed for structural stainless steel plate, rather than for reinforcement bars. Current design guidance for material modelling of reinforcing bars does not include representative stress-strain relationships which capture the unique mechanical properties of stainless steel reinforcement. Codes include idealised elastic-plastic material models which are inappropriate and inefficient for the highly nonlinear and ductile material response of stainless steel. The present study aims to address this issue by first conducting a series of tensile tests to ascertain the stress-strain material responses and then employing this data to examine the validity of existing approaches and propose new material models where required. It is shown that new material models are required and those that are developed are able to accurately capture the stress-strain response of stainless steel reinforcement, and provide a better, more accurate, representation than existing methods.

1. Introduction

This paper is focussed on the mechanical characterisation of austenitic and duplex stainless steel reinforcement for use in structural analysis and design. These materials are increasing in popularity and interest owing to their outstanding corrosion resistance, mechanical properties and life cycle performance [1]. Compared with more traditional carbon steel reinforcement, stainless steel rebars are significantly more ductile, can offer great strength and also have very good fire resistance. The ductility properties are very attractive in particular during extreme scenarios such as an earthquake or blast as the ability for structures to endure high levels of deformation and damage compared with traditional reinforced concrete structures may facilitate the redistribution of loads and stresses in the structure, thus avoiding or delaying collapse [2,3].

Stainless steel reinforced concrete has been available to designers for a number of years as a structural solution, but until recently was mainly employed in applications where corrosion resistance was required. However, now there are ever-increasing demands to enhance the durability and resilience of reinforced concrete (RC) structures, to extend their useful design life and also to minimise expensive inspection and maintenance requirements. In this context, the use of inherently durable and resilient stainless steel in place of carbon steel rebars is growing, predominantly driven by concerns and the economic implications related to reinforcement corrosion,

* Corresponding author.
E-mail address: k.cashell@ucl.ac.uk (K.A. Cashell).

https://doi.org/10.1016/j.cscm.2024.e03013
Received 24 October 2023; Received in revised form 16 February 2024; Accepted 22 February 2024
Available online 23 February 2024

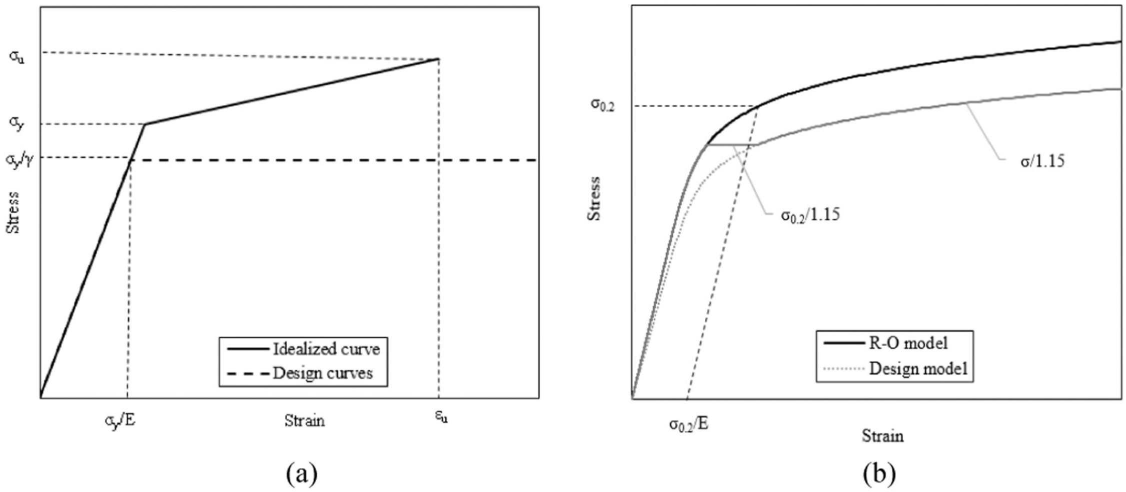

Fig. 1. Idealized stress-strain curves as given in (a) Eurocode 2 [36] and (b) BS 6744 [37].

concrete carbonation and environmental impact [4]. The costs associated with inspection, repair, maintenance, and replacement of deteriorating structures and infrastructure can impose significant pressures on government resources, and can result in disruptions which adversely affect productivity and local economic well-being. In some cases, corrosion may impair the structural integrity and functionality of a structure due a reduction in the steel area and strength, and consequently reduce the ductility, structural stiffness and load bearing capacity of the affected members [5]. Therefore, incorporating stainless steel reinforcement in RC structures provides a more durable long-lasting alternative to traditional carbon steel reinforced concrete, thus potentially extending the design life of structures, reducing the embodied carbon costs and decreasing the economic costs and disruption related to inspection, monitoring, maintenance and rehabilitation works [6,7].

The increasing interest in stainless steel reinforced concrete has led to greater attention being directed towards its structural performance within the engineering research community. The vast majority of research in the available literature has focussed on the corrosion resistance and durability [8–11]. There has been a very limited amount of research into the material properties, including the proposal of a material model to represent the compressive stress-strain response for design and analysis [12] and also a study into the behaviour at elevated temperature [13]. It is notable that the amount of test data for stainless steel reinforcement is significantly less than for bare structural stainless steel. Research has been conducted into the bond behaviour between stainless steel reinforcement and the surrounding concrete for reinforced concrete (RC) members [5,14–16] as well as a limited number of tests on RC beams [17–20] and columns [21,22]. A novel design approach has been recently proposed by Rabi et al. [6,23] to harness the distinctive strain hardening and ductility properties of stainless steel reinforcement into the design of reinforced concrete members.

There are various material models that have been developed in recent decades to describe this nonlinear stress-strain behaviour of structural stainless steel [e.g. 24–31]. These are generally based on the expression originally developed by Ramberg-Osgood (R-O) [24] and modified later by Hill [25]. The models require a number of key parameters to be defined to characterise the response, which are obtained from experimental stress-strain curves. The values of these parameters are given in design standards such as EN 1993–1–4 [26], through tables and predictive expressions. However, the applicability of these material models has not yet been evaluated for stainless steel reinforcement and they are not included in the corresponding RC design codes (e.g. Eurocode 2).

A comprehensive review of the current knowledge and available design guidance pertaining to the use of stainless steel reinforcement in concrete structures was conducted [1]. It was concluded that there is a lack of information and data in the literature on the constitutive behaviour of austenitic and duplex stainless steel reinforcement, as well as on appropriate material models and associated characteristic parameters, as required for both the analysis and design of stainless steel reinforced concrete structures. Given the high initial costs of stainless steel reinforcement compared with that of carbon steel, as well as the increasingly important desire to use raw materials with efficiency, it is imperative that an accurate description of the stress-strain relationship is available for use in the design of RC structures. It is also important from a performance point of view, to ensure that analysis of these members is accurate and reliable. In this context, the current paper presents the results from a series of tensile tests on different grades of stainless steel reinforcement, as available from local stockholders. The paper employs this data, as well as other available results from the literature [5,13,17], to assess the accuracy of current stainless steel material models, which were largely developed for structural stainless steel plate, for representing the stress-strain constitutive relationship of stainless steel reinforcement. Finally, a new rebar-specific material model is proposed based on the data gathered.

2. Material modelling of stainless steel

Stainless steel reinforcement exhibits a continuous, nonlinear constitutive behaviour without a clearly defined yield point as well as significant strain hardening. This is fundamentally different from the stress-strain behaviour of carbon steel, which typically has an elastic-plastic, or elastic-linear hardening response with a clearly-defined yield point and little to moderate strain hardening. The current design rules for RC members in global design standards, such as Eurocode 2 [27], include an elastic-plastic stress-strain model as well as elastic-linear hardening model for the design of RC members, as shown in Fig. 1(a). The former of these models is suitable in most cases for the design of carbon steel RC members but is not reflective of the nonlinear, ductile response of stainless steel, whilst the elastic-linear hardening model is applicable only up to a limiting strain value set in the standard which is significantly below the ultimate strain of stainless steel reinforcement.

BS 6744 [28] advises that employing the idealized constitutive relationships as outlined in Eurocode 2 [36] might not be suitable for stainless steel RC design applications owing to the different stress-strain response. Instead, it suggests using a nonlinear model based on the original Ramberg-Osgood (R-O) expression [24], as shown in Fig. 1(b). The original Ramberg-Osgood (R-O) expression for representing the relationship between the engineering stress (σ) and the engineering strain (ε) is presented in Eq. 1, in which $\sigma_{0.2}$ is the 0.2% proof stress determined by drawing a line with a slope equal to the elastic modulus or Young's modulus (E) between 0.2% strain ($\varepsilon_{0.2}$) on the x-axis and the stress-strain curve. n is the strain hardening exponent calculated from Eq. 2 and $\sigma_{0.01}$ is the 0.01% proof stress corresponding to a 0.01% strain.

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

$$n = \frac{\ln(20)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \tag{2}$$

It was observed that employing the original R-O model provides accurate results for stresses up to the 0.2% proof stress. However, it overestimates the stresses in the post-yield range (i.e., beyond the 0.2% proof stress) and is therefore inappropriate for representing the full stress-strain relationship of stainless steel [20,29–32].

Therefore, several material models were developed to accurately predict the full stress-strain response. Mirambell and Real [33] proposed a two-stage material model including the original Ramberg-Osgood expression (Eq. 2) for stresses below the 0.2% proof stress and a second curve for stresses beyond the 0.2% proof stress, as given in Eq. 3.

$$\varepsilon = \varepsilon_{0.2} + \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m \quad for \quad \sigma_{0.2} < \sigma \leq \sigma_u \tag{3}$$

$$E_{0.2} = \frac{E}{1 + 0.002n\frac{E}{\sigma_{0.2}}} \tag{4}$$

In these expressions, ε and σ are the engineering strain and stress, respectively, $E_{0.2}$ is the tangent modulus at the 0.2% proof stress calculated from Eq. 4, σ_u and ε_u are the ultimate stress and corresponding ultimate strain, respectively, $\varepsilon_{0.2}$ is the strain corresponding to $\sigma_{0.2}$ and m is the second strain hardening exponent.

Additional simplifications to this model were proposed by Rasmussen [34] for the post-yield portion of the response, to reduce the number of the parameters required. The basic assumption is that the ultimate plastic strain ($\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_{0.2}}$) is equal to total ultimate strain ε_u, as expressed in Eq. 5. Rasmussen [34] also included predictive expressions for the determination of the strain hardening parameter m, the ultimate strain and the ultimate strength as given in Eq. 6-8, respectively. This results in a reduction in the number of parameters required to three basic Ramberg–Osgood parameters (E, $\sigma_{0.2}$ and n). It is worth noting that this proposal was included in EN 1993–1–4, Annex C [26] for representing the material behaviour of stainless steel.

$$\varepsilon = \varepsilon_{0.2} + \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m \quad for \quad \sigma_{0.2} < \sigma \leq \sigma_u \tag{5}$$

$$m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u} \tag{6}$$

$$\varepsilon_u = 1 - \frac{\sigma_{0.2}}{\sigma_u} \tag{7}$$

$$\begin{aligned} &\frac{\sigma_{0.2}}{\sigma_u} = 0.20 + 185\frac{\sigma_{0.2}}{E} && \text{for austenitic and duplex stainless steels} \\ &\frac{\sigma_{0.2}}{\sigma_u} = \frac{0.20 + 185\frac{\sigma_{0.2}}{E}}{1 - 0.0375(n-5)} && \text{for all other stainless steel grades} \end{aligned} \tag{8}$$

Gardner and Nethercot [35] introduced additional modifications allowing the model to be used for compression and improving the accuracy of the model at low strains (i.e. below 10%). These modifications involve employing the 1% proof stress ($\sigma_{1.0}$) instead of the ultimate strength (σ_u) in Eq. 1, as given in Eq. 9, where the strain hardening exponent is denoted as $n_{0.2,1.0}$.

$$\varepsilon = \varepsilon_{0.2} + \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_{1.0} - \varepsilon_{0.2} - \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}}\right)^{n_{0.2,1.0}} \tag{9}$$

Table 1
A summary of the material properties obtained from the current test programme and existing data available in the literature for austenitic and duplex stainless steel reinforcement.

Stainless steel type	Grade	Diameter (mm)	No. of tests	$\sigma_{0.01}$(N/mm^2)	$\sigma_{0.2}$(N/mm^2)	σ_u(N/mm^2)	ε_u(%)	E (N/mm^2)	n	m
Current test programme										
Austenitic	1.4301	8	9	367	727	909	23.4	184144	4.9	11.0
		10	2	390	647	833	19.7	157675	5.6	4.9
		12	7	389	656	799	14.1	177060	6.3	11.0
	1.4401	12	3	327	599	722	15.6	166457	6.2	10.3
	1.4404	8	3	402	680	803	14.1	170307	6.2	14.9
	1.4436	6	2	394	695	821	10.2	172580	5.4	7.2
		8	2	345	576	800	22.8	188735	6.7	4.4
		10	2	322	619	753	12.7	165325	5.3	7.9
		12	2	354	637	781	19.7	172785	5.6	13.6
		16	2	239	444	664	30.0	198035	5.8	4.0
	1.4571	6	2	324	585	735	17.0	181040	5.4	6.5
		8	1	348	613	784	19.0	170520	5.7	7.1
		12	2	290	586	746	15.5	174815	4.4	15.0
Duplex	1.4362	6	2	427	780	935	2.3	163465	4.8	6.6
		8	8	438	729	888	10.5	151574	6.1	6.3
		12	3	466	806	951	8.1	158353	6.3	6.2
		16	2	381	639	822	20.0	182680	5.7	5.3
	1.4482	8	2	307	744	919	30.2	185625	4.2	2.7
		10	2	344	820	1057	25.4	163690	3.7	2.8
		12	2	323	764	989	22.0	189045	3.7	2.9
Test data from the literature										
Austenitic [5]	1.4301	10	3	328	513	787	30.4	189699	7.6	3.4
		12	2	413	707	869	14.3	177055	5.6	7.4
Austenitic [13]	1.4307	12	1	301	595	796	30.7	155690	6.1	6.1
		16	1	252	542	751	31.4	203120	8.1	1.4
	1.4311	12	1	214	479	764	38.6	210970	3.8	4.1
		16	1	288	526	817	32.9	205880	5.7	3.9
Duplex [13]	1.4362	16	2	390	683	847	12.1	187265	6.1	5.6
	1.4162	12	3	466	717	894	15.3	189063	7.6	6.2
Austenitic [17]	1.4301	8	3	357	732	902	20	184147	4.5	12.2
		10	3	392	644	799	31	164563	5.9	5.9
		12	3	450	708	876	16	169737	6.5	9.1
	1.4401	8	3	298	588	820	29	223850	5.2	5.0
		10	3	422	655	793	16	168903	6.7	8.7
		12	3	383	653	801	14	188413	6.1	12.4

Building on these developments of the original Ramberg-Osgood material model, researchers also proposed more multi-stage models which may be appropriate in particular circumstances such as analysing connection behaviour or incorporating the effects of cold forming. Quach et al. [36] proposed a three-stage material model that implements the original Ramberg–Osgood expression [24] as given in Eq. 1 for stresses up to 0.2% proof stress, the Gardner and Nethercot [35] expression as in Eq. 9 for stresses between the 0.2% proof stress and the 2.0% proof stress and then a straight line up to the ultimate stress. An alternative three-stage model was proposed by Hradil et al. [37] which employs the original Ramberg–Osgood expression for every stage using a different reference system.

It was found that the three-stage models offer a better depiction of the experimental stress-strain curves compared with the two-stage models, but require a greater number of the input parameters from the user. Therefore, the two-stage models suggested by Mirambell and Real [33] and Rasmussen [34] offer more practicality for use in real-life engineering applications, attaining a high level of accuracy with fewer input parameters required by the user. A comparative study conducted by Arrayago et al. [29] showed that the material model proposed by Rasmussen [34] is more appropriate for high ductility stainless steels such as austenitic and duplex grades since the disparity between the omitted term ($\varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_{0.2}}$) and the total ultimate strain (ε_u) is negligible. However, a further assessment is required for low-ductility stainless steel, such as the ferritic grades or materials that are cold-worked. Given that, all stainless steel reinforcement that is currently commercially available is either an austenitic or duplex stainless steel grade, the model proposed by Rasmussen [34] achieves an excellent balance between practicality and accuracy and thus is selected herein for analysis and assessment of the key material parameters.

It is worth noting that researchers have also successfully employed much simpler stress-strain curves, including bi-linear models [6], for stainless steel in reinforced concrete design in order to avoid the complexity of implementing the nonlinear stress-strain behaviour in analysis. This approach is given in the following expressions:

$$\sigma = E\varepsilon \quad \varepsilon \le \varepsilon_y \tag{10}$$

$$\sigma = \sigma_{0.2} + E_{sh}(\varepsilon - \varepsilon_y) \quad \varepsilon > \varepsilon_y \tag{11}$$

Fig. 2. Stainless steel reinforcement bars before tensile testing.

The yield strain ε_y is defined 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. 12:

$$E_{sh} = \frac{\sigma_u - \sigma_{0.2}}{C_2\varepsilon_u - \varepsilon_y} \quad (12)$$

Following an extensive parametric study [6,23], a value for E_{sh} ranging between 0.15 and 0.3 was found to be appropriate for stainless steel RC beams, depending on the grade. Although this model provides a straight forward representation which might be appropriate in design, it is clearly not reflective of the true stress-strain response and it is crucially important to have a predictive material model which represents the full constitutive stress-strain relationship for stainless steel reinforcement.

3. Experimental programme

A total of 60 tensile tests were conducted in this study on various grades of stainless steel reinforcement with different diameters, and these are listed in Table 1. At least two repeats were conducted for each bar type, with more repeats conducted if the results were incompatible. The tensile tests were carried out in accordance with BS EN 6892–1 [38], using a 300 kN Tinius Olsen universal test machine. The specimens were examined under displacement control, with a strain rate of 0.1 mm/min for strains up to 1.0% and then 2.2 mm/min until the fracture stress. The strain in the material was measured over a gauge length of 50 mm in the middle of the test coupon. The test was paused briefly in order to remove the extensometer. An image of the test samples before testing is presented in Fig. 2. It is noteworthy that all of the test material was obtained from local stockholders in the London region, in order to determine realistic properties for material employed in real projects.

The measured stress-strain response for different grades of stainless steel reinforcement are presented in Fig. 3, separated into different graphs for each diameter of bar examined. For each specimen, the 0.01 ($\sigma_{0.01}$) and 0.2% ($\sigma_{0.2}$) proof stresses were obtained by identifying the intersection points between the stress-strain curve and the offset lines of the modulus of elasticity E which passes through the 0.01% and the 0.2% strain at the x-axis, respectively. The modulus of elasticity was carefully calculated from a linear regression analysis. The ultimate stress σ_u and corresponding ultimate strain ε_u were also identified. The average values for each of these properties, for each bar type, are presented in Table 1. In addition to these test data, a total of 32 other tests were also available in the literature [5,13,17] and the results from these are also presented in Table 1, and discussed herein. It is important to note that these are the only test data that were found which presented the full stress-strain response, including at low strains in order to determine E and $\sigma_{0.2}$. In relation to the failure mode, it is noteworthy that failure location is quite challenging for rebars, as fracture can occur anywhere along the member length, outside of a specific gauge length. In these tests, fracture occurred at different locations along the bar length, but away from the grips in all cases. From the test results, the mean Young's modulus values are found to be 176.9 kN/mm^2 and 164.6 kN/mm^2 for austenitic and duplex reinforcements respectively. Slightly higher values were observed in previous test results reported in Table 1 with mean values of 185.1 kN/mm^2 and 188.3 kN/mm^2 for austenitic and duplex stainless steel reinforcement, respectively. There are several recent studies which have shown similar observations low Young's modulus values for stainless steel reinforcement [e.g. [2,3,19,39,40]]. Nevertheless, it is recommended that this property is explored in greater detail, with reliability analyses, in the future. Additionally, austenitic grade 1.4301 and duplex grade 1.4482 stainless steel are shown to have the highest ultimate stress among the tests performed in this programme. Similar observations were found in the tests obtained from the literature for grade 1.4301. It is also observed that the most ductile austenitic and duplex stainless steel rebars from the test programme conducted in the current work are grade 1.4436 and 1.4482, respectively, while for the tests from the literature the corresponding grades are grades 1.4311 and 1.4162.

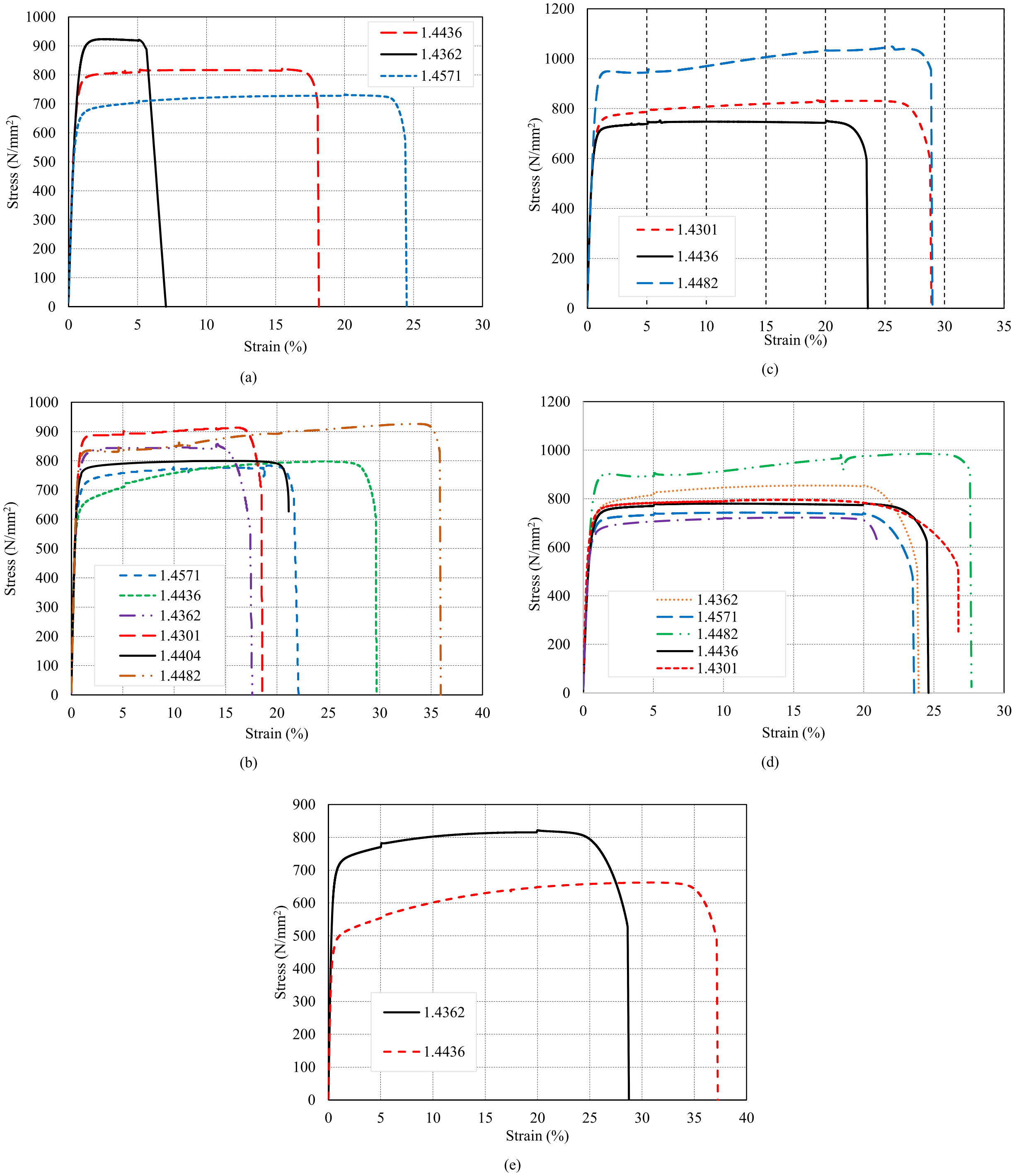

Fig. 3. Measured stress-strain curves for different austenitic and duplex stainless steel grades with reinforcement diameters of (a) 6 mm, (b) 8 mm, (c) 10 mm, (d) 12 and (e) 16 mm.

4. Test results and analysis

In this section, the experimental constitutive stress-strain curves discussed previously are analysed to obtain the key parameters of the material model for different stainless steel grades. As stated before, the limited number of test results available in the literature [5,13,17] are also employed in the current section for further assessment and validation of material model parameters. The applicability of the different predictive expressions proposed by Rasmussen [34] and given in EN 1993–1–4 [26] for bare stainless steel sections are

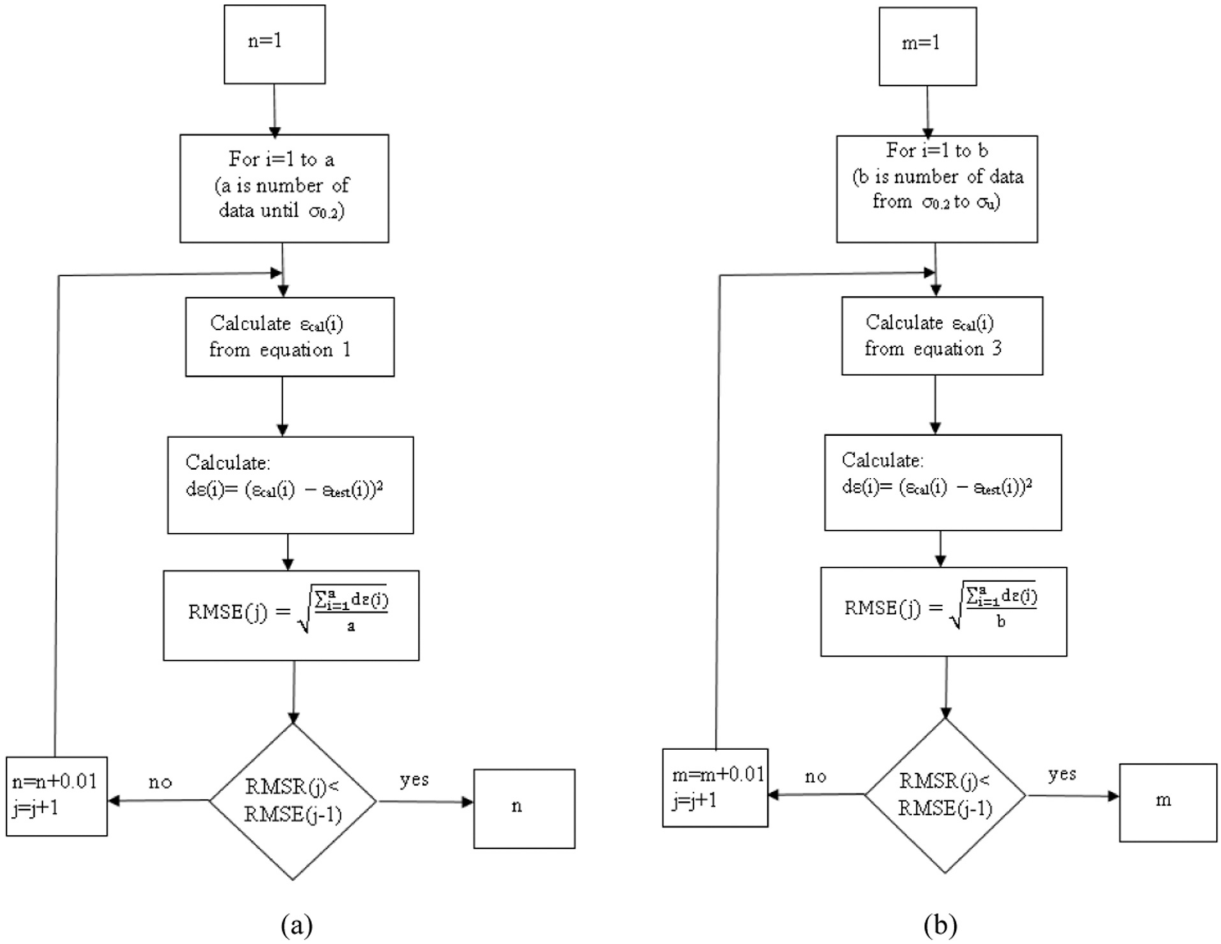

Fig. 4. Flow chart of the various steps implemented in the MATLAB code developed to determine (a) n and (b) m.

investigated for stainless steel reinforcement, with particular attention given to the strain hardening exponents (n and m), the ultimate stress f_u and the ultimate strain ε_u.

Determination of the optimum values for the strain hardening exponents n and m from experimental stress-strain curves involves complex calculations. In order to simplifying the optimisation process and automating the calculations, a MATLAB programme [41] was developed, offering accurate results at low computational cost. This is achieved by using a least square adjustment technique to find the optimum values of the strain hardening exponents n and m that allow the material model to precisely depict the experimental stress-strain curve through iteratively adjusting these values to achieve a relative error convergence between the R-O expression and experimental data. A flow chart describing the routine developed using MATLAB is presented in Fig. 4.

4.1. *Strain hardening exponent n*

Two different expressions for calculating n are proposed in the literature and are assessed here. The first was developed by Ramberg-Osgood (R-O) [24] and was previously presented in Eq. 2; this is adopted in EN 1993–1–4 [26] for structural stainless steel. The second method, which is originally proposed by Rasmussen and Hancock [42], employs the 0.05% proof stress instead of the 0.01% proof stress as it is suggested that this provides a better representation of the experimental stress-strain behaviour of stainless steel [43,44,29,33] and is presented in Eq. 13:

$$n = \frac{\ln(20)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.05}}\right)} \tag{13}$$

For both cases, the experimental data has been assessed and the first strain hardening component n was determined by employing a least square adjustment through experimental curve fitting; the calculated value is denoted as n_{exp}. On the other hand, the predicted values using Eqs. 2 and 13 are referred to as n_{pred}. The results are presented in Fig. 5 and also Table 2.

It is observed that the n values determined from the experimental data using Eq. 2 are excellent with a close agreement between

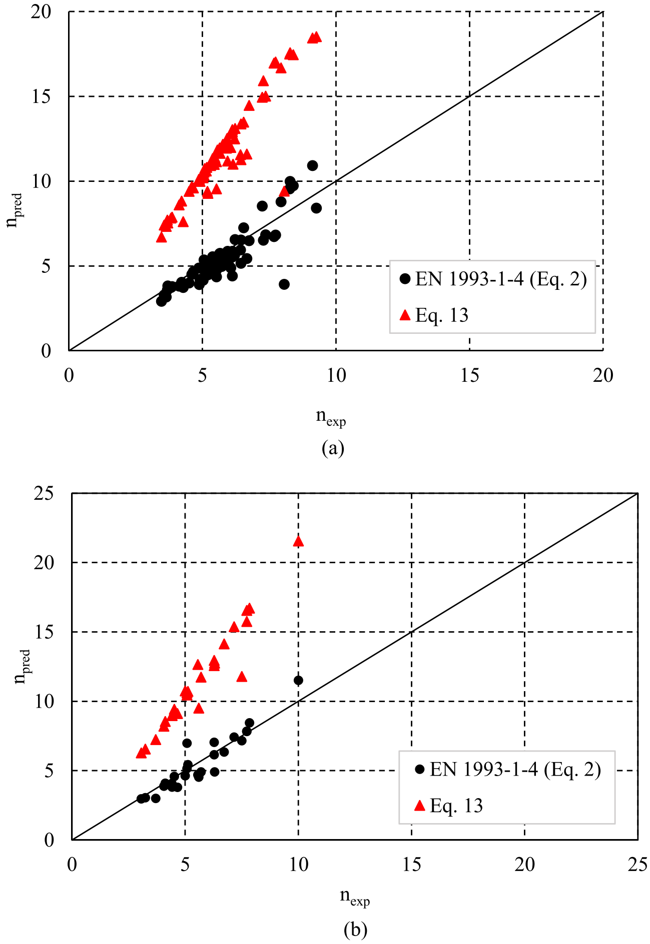

Fig. 5. Comparison of the predicted and experimental strain hardening exponent n for (a) austenitic and (b) duplex stainless steel reinforcement.

Table 2
Assessment of the predicted and experimental first strain hardening exponent n.

Stainless steel type		Eq. 2 [26] n_{pred}/n_{exp}	Eq. 13 [42] n_{pred}/n_{exp}
Austenitic	Mean	0.94	2.02
	RMSE	0.88	6.16
	COV	0.12	0.08
Duplex	Mean	0.97	2.04
	RMSE	0.72	6.21
	COV	0.13	0.07

n_{exp} and n_{pred}. The mean n_{pred}/n_{exp} ratio, root mean square error (RMSE) and coefficient of variation (COV) values are 0.94, 0.88 and 0.12 for austenitic stainless steel, respectively, and 0.97, 0.72 and 0.13 for duplex stainless steel, respectively. In contrast, Eq. 13 tends to overestimate the corresponding experimental values with mean n_{pred}/n_{exp} ratio, RMSE and COV values of 2.02, 6.16 and 0.08, respectively, for austenitic stainless steel, and 2.04, 6.21 and 0.07 for duplex stainless steel, respectively. It is obvious that the RMSE for Eq. 13 is significantly higher than that of the Eq. 2 by a factor of approximately 6× and 8× for austenitic and duplex reinforcement, respectively, indicating less accurate predictions. Therefore, it is concluded that although there is less scatter when Eq. 13 is employed compared with Eq. 2, as evidenced by lower COV values, it provides quite inaccurate and un-conservative predictions for the n exponent for stainless steel reinforcement.

Numerical values of n based on the average experimental data have been determined for each stainless steel reinforcement grade and compared with the values for structural stainless steel as given in 1993–1–4 (n_{EC3}) [26]. A comparison of the results is presented in Table 3. These values are relatively different from those proposed in Gardener et al. [13], which are 4.7 and 5.3 for austenitic and duplex stainless steel reinforcement. It is worth noting that the recommended values of n are proposed without specifying the loading

Table 3
Recommended values for the first strain hardening exponent n.

Stainless steel reinforcement type	Grade	n_{EC3} [26]	Recommended n
Austenitic	1.4301	6	5.8
	1.4401	7	6.1
	1.4404	7	6.2
	1.4436	-	5.8
	1.4571	7	5.1
	1.4307	6	7.1
	1.4311	-	4.8
Duplex	1.4362	5	5.9
	1.4482	-	3.9
	1.4162	-	7.6

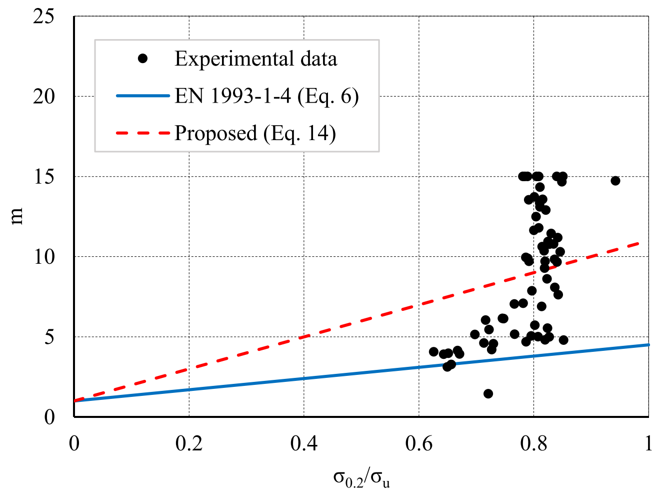

Fig. 6. Assessment of different predictive models for the strain hardening exponent m for austenitic stainless steel reinforcement.

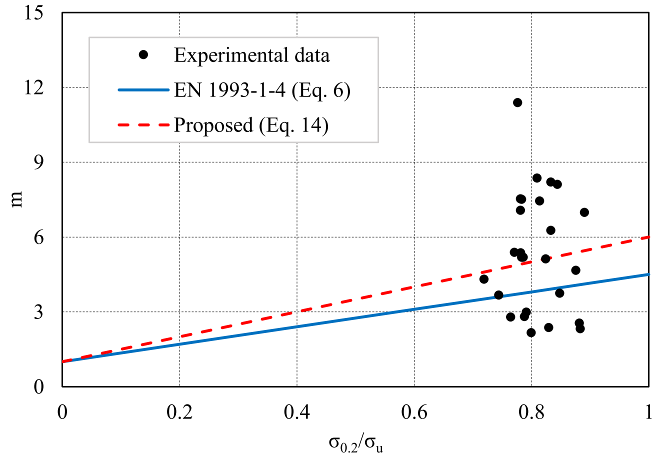

Fig. 7. Assessment of different predictive models for strain hardening exponent (m) for duplex stainless steel reinforcement.

direction (i.e. transverse or longitudinal loading) as this information is not available.

4.2. Strain hardening exponent m

The accuracy of the expression presented in Eq. 6 and provided in EN 1993–1–4 [26] for the determination of the strain hardening exponent m (referred to herein as m_{pred}) is assessed through a comparison with the experimental strain hardening exponent (m_{exp}) for austenitic and duplex stainless steel reinforcement, as shown in Fig. 6 and Fig. 7. As before, m_{exp} was determined by a least square

Table 4
Assessment of the predicted and experimental strain hardening exponent m.

Stainless steel rebar type		[Eq. 6 [26]](#) m_{pred}/m_{exp}	**Eq. 14** m_{prop}/m_{exp}
Austenitic	Mean	0.54	1.26
	RMSE	6.43	3.62
	COV	0.60	0.60
Duplex	Mean	0.89	1.17
	RMSE	2.81	2.39
	COV	0.49	0.49

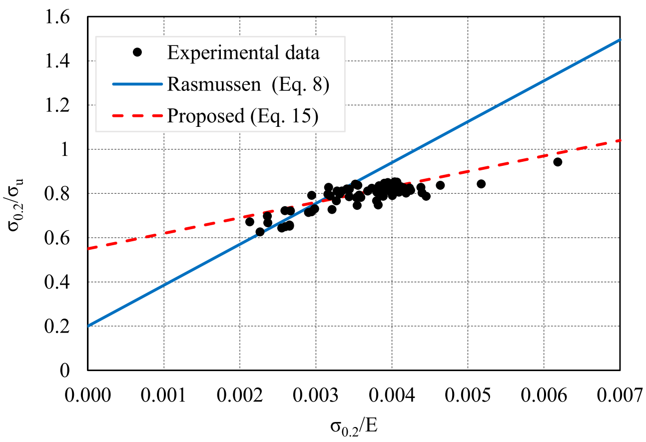

Fig. 8. Assessment of different predictive models for ultimate stress (σ_u) of austenitic stainless steel reinforcement.

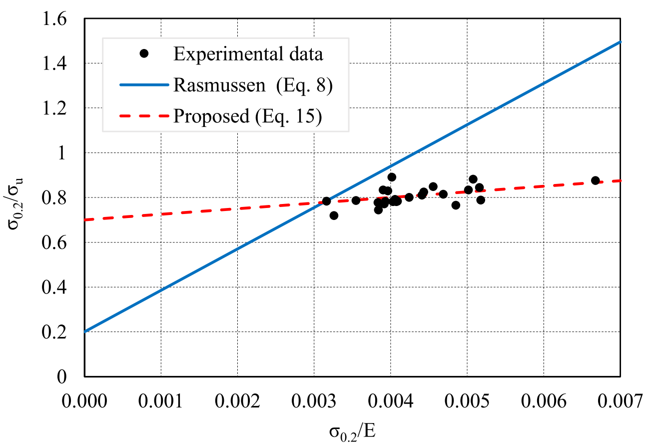

Fig. 9. Assessment of different predictive models for ultimate stress (σ_u) of duplex stainless steel reinforcement.

adjustment method through experimental curve fitting to the R-O expression considering Eq. 6, and a MATLAB routine was devised for this purpose. The results are also presented in Table 4.

It is observed that Eq. 6 [26] for austenitic structural stainless steel plate provides very conservative results for austenitic stainless steel reinforcement. The mean m_{pred}/m_{exp} ratio, RMSE and COV values are 0.54, 6.43 and 0.6, respectively, whilst the corresponding values for duplex stainless steel reinforcement are 0.89, 2.81 and 0.49, respectively. Therefore, a new expression is proposed to determine an appropriate m value for stainless steel reinforcement (m_{prop}) using a linear regression analysis and is given in Eq. 14. It is observed that the proposed expression is capable of providing better predictions based on the experimental results for austenitic stainless steel reinforcement with mean m_{prop}/m_{exp}, RMSE and COV values of 1.26, 3.62 and 0.6, respectively. These corresponding values for duplex stainless steel reinforcement are 1.17, 2.39 and 0.49, respectively. Although a similar scatter is found when either Eq. 13 or Eq. 6 is employed, as indicated by the COV values, the RMSE for Eq. 6 is 78% and 18% greater than that of Eq. 14 for austenitic and duplex reinforcement, indicating less accurate predictions. As shown, the performance of the proposed expression is better than

Table 5
Assessment of the predicted and experimental ultimate strength.

Stainless steel reinforcement type		Eq. 8 [26] $\sigma_{u,pred}/\sigma_{u,exp}$	Eq. 15 $\sigma_{u,prop}/\sigma_{u,exp}$
Austenitic	Mean	0.92	0.98
	RMSE	101.90	40.14
	COV	0.09	0.05
Duplex	Mean	0.80	1.00
	RMSE	219.73	38.73
	COV	0.13	0.04

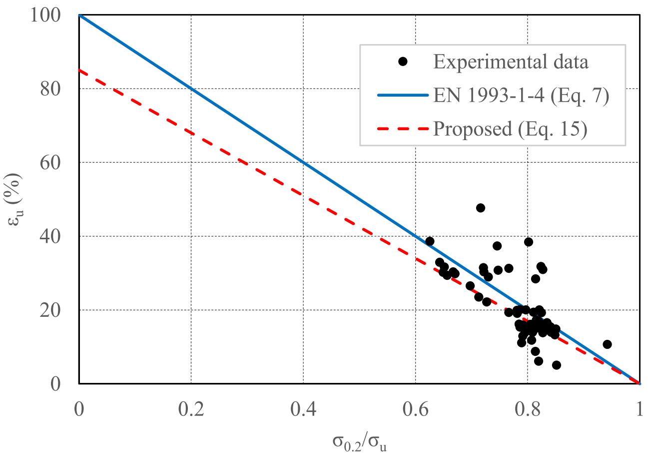

Fig. 10. Assessment of different predictive models for the ultimate strain (ε_u) of austenitic stainless steel reinforcement.

that of Eq. 6, providing more accurate mean value of the predicted-to-experimental ratio with lower relative errors. Hence, the proposed expression (Eq. 14) is recommended to use for stainless steel reinforcement.

$$m_{prop} = 1 + 10\frac{\sigma_{0.2}}{\sigma_u} \text{ for austenitic stainless steel reinforcement,} \quad m_{prop} = 1 + 5\frac{\sigma_{0.2}}{\sigma_u} \text{ for duplex stainless steel reinforcement} \tag{14}$$

4.3. *Ultimate stress σ_u*

This section assesses the accuracy of employing the expression proposed by Rasmussen [34] and presented in Eq. 8 for predicting the ultimate stress σ_u of structural stainless steel, for stainless steel reinforcement. In this equation, σ_u is determined as a function of $\sigma_{0.2}$ and E for austenitic and duplex stainless steels. The results are presented in Figs. 8 and 9, and are also tabulated in Table 5, where $\sigma_{u,exp}$ are experimental values, $\sigma_{u,pred}$ are the ultimate stress values calculated using Eq. 8 and $\sigma_{u,prop}$ are new predictions for the ultimate stress using the proposed expression in Eq. 15. This expression was developed specifically based on the experimental data for stainless steel reinforcement using a linear regression analysis, as described previously. The results are presented in terms of $\sigma_{0.2}/E$ *versus* $\sigma_{0.2}/\sigma_u$.

It is observed that the expression given in Eq. 8 [34] tends to give inappropriate predictions of the ultimate stress compared with the experimental data for rebars, particularly for duplex stainless steel reinforcement. The mean $\sigma_{u,pred}/\sigma_{u,exp}$, RMSE and COV values for austenitic stainless steel reinforcement based on Eq. 8 are 0.92, 101.9 and 0.9, respectively whilst the corresponding values for duplex stainless steel reinforcement are 0.8, 219.7 and 0.13, respectively. Although the mean values are relatively acceptable, the RMSE values are very large, indicating a lack of accuracy. On the other hand, the same values using the new proposed expression given in Eq. 15 for the mean $\sigma_{u,prop}/\sigma_{u,exp}$, RMSE and COV values for austenitic stainless steel reinforcement are 0.98, 40.1 and 0.05, respectively whilst the corresponding values for duplex stainless steel reinforcement are 1.0, 38.7 and 0.04, respectively. Based on these results, it is clear that the RMSE for Eq. 8 is significantly higher than the corresponding values obtained using Eq. 15, indicating that Eq.8 provides less accurate predictions compared with Eq. 15. Eq. 15 is derived using data from stainless steel reinforcement whereas Eq. 8 was developed from data on bare stainless steel plate, which clearly results in different ultimate behaviour.

$$\frac{\sigma_{0.2}}{\sigma_{u,prop}} = 0.55 + 70\frac{\sigma_{0.2}}{E} \text{ for austenitic stainless steel reinforcement}$$

$$\frac{\sigma_{0.2}}{\sigma_{u,prop}} = 0.7 + 25\frac{\sigma_{0.2}}{E} \text{ for duplex stainless steel reinforcement} \tag{15}$$

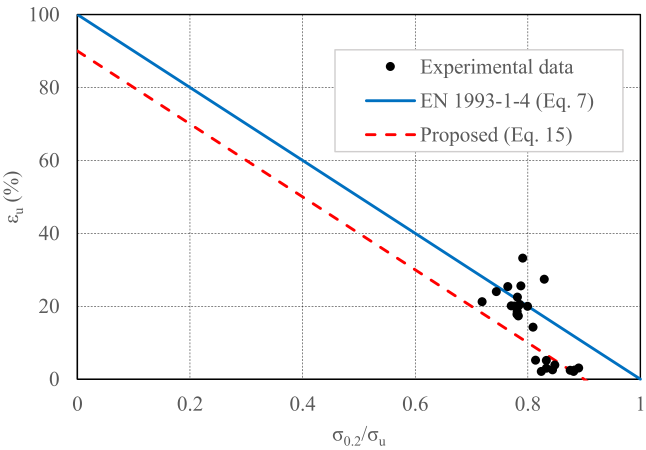

Fig. 11. Assessment of different predictive models for ultimate strain (ε_u) of duplex stainless steel reinforcement.

Table 6
Assessment of the predicted and experimental for ultimate strain.

Stainless steel type		Eq. 7 [26] $\varepsilon_{u,pred}/\varepsilon_{u,exp}$	Eq. 16 $\varepsilon_{u,prop}/\varepsilon_{u,exp}$
Austenitic	Mean	1.17	0.99
	RMSE	6.28	6.59
	COV	0.36	0.36
Duplex	Mean	2.60	0.94
	RMSE	8.34	8.80
	COV	0.84	0.79

4.4. Ultimate strain ε_u

The ultimate strain values from the experimental data $\varepsilon_{u,exp}$ are compared with the values determined using the expression for structural stainless steel as given in EN 1993–1–4 [26] and Eq. 7 ($\varepsilon_{u,pred}$), as shown in Fig. 10 for austenitic stainless steel reinforcement and Fig. 11 for duplex stainless steel rebars. The results are presented in terms of the ultimate strain versus the $\varepsilon_{0.2}/\varepsilon_u$ ratio. In addition, the corresponding numerical values are given in Table 6. It is observed that Eq. 7 generally overestimates the ultimate strain values with mean $\varepsilon_{pred}/\varepsilon_{exp}$, RMSE and COV values of 1.17, 6.28 and 0.39 for the austenitic rebars and 2.6, 8.34 and 0.84 for the duplex stainless steel grades, respectively. These values are quite unconservative (i.e. are on the unsafe side), particularly for duplex stainless steel reinforcement. As with the other mechanical properties, in order to provide a better representation of the ultimate strain of stainless steel reinforcement, a new expression is proposed to determine $\varepsilon_{u,prop}$ based specifically on data from rebar tensile tests using a linear regression analysis and this is given in Eq. 16:

$$\varepsilon_{u,prop}(\%) = 0.85\left(1 - \frac{\sigma_{0.2}}{\sigma_u}\right) \text{ for austenitic stainless steel reinforcement}$$

$$\varepsilon_{u,prop}(\%) = \left(0.9 - \frac{\sigma_{0.2}}{\sigma_u}\right) \text{ for duplex stainless steel reinforcement} \tag{16}$$

The results using Eq. 16 are also presented in Figs. 10 and 11 and Table 6, for comparison. It is observed that the proposed expression provides a more accurate prediction of the ultimate strain for both austenitic and duplex stainless steel reinforcement compared with the existing expressions for structural stainless steel. The mean $\varepsilon_{u,prop}/\varepsilon_{exp}$, RMSE and COV values are 0.99, 6.59 and 0.36 for austenitic rebars and 0.94, 8.8 and 0.79 for the duplex stainless steel grades, respectively. Although the degree of accuracy and scatter of the predictions are relatively similar for both equations, the mean predicted-to-experimental value is improved by around 18% and 175% when Eq. 16 is employed for austenitic and duplex reinforcement, respectively, compared with Eq. 7. It is deduced that the proposed expression provides more accurate predictions for the ultimate strain for both austenitic and duplex stainless steel reinforcement, with less scatter than existing methods which were not developed for rebars.

5. Comparisons with experimental stress-strain responses

Following the earlier discussions on the key constitutive properties for austenitic and duplex stainless steel reinforcement, the current section takes an overall view of the proposed material model in terms of the shape as well as strength, stiffness and strain

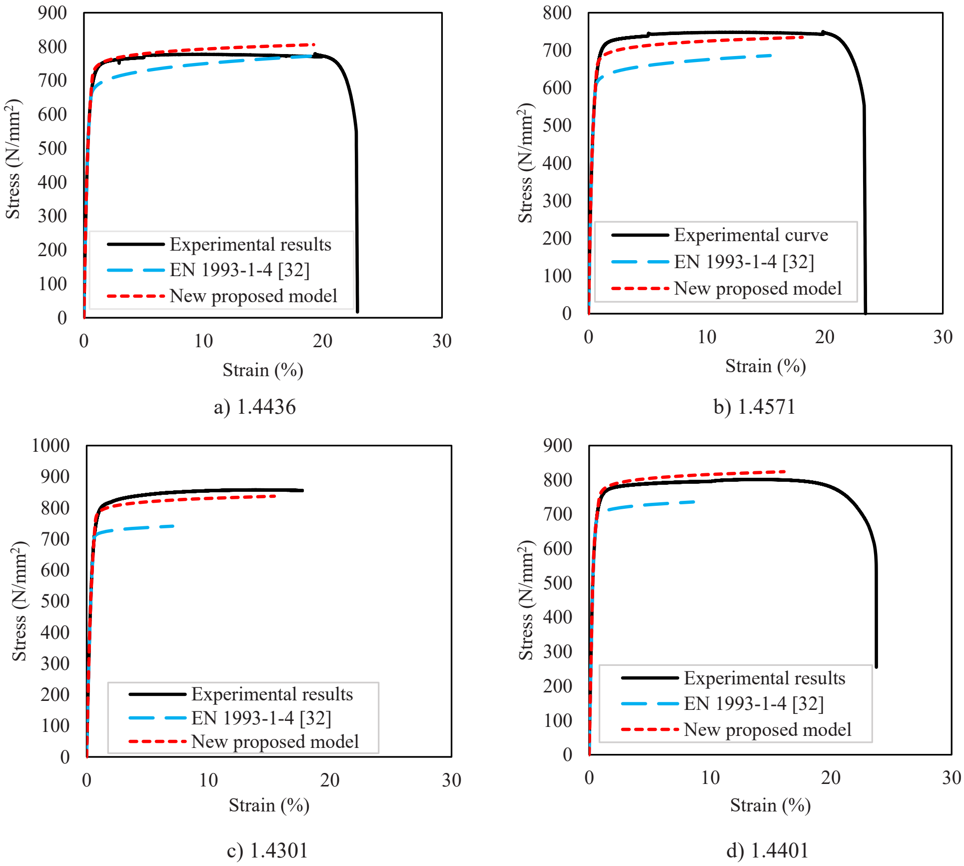

Fig. 12. Comparison of the proposed material model for 12 mm austenitic stainless steel reinforcement and the method currently included in EN 1993–1-4 [26] for structural stainless steel plate.

characteristics, compared with experimental data. The proposed expressions for n, m, σ_u and ε_u (i.e. n, m_{prop}, σ_{prop} and $\varepsilon_{u,prop}$ as given in Eq. 2, 14, 15 and 16) are employed to predict the responses for the austenitic and duplex grades examined in the aforementioned test programme in Figs. 12 and 13, respectively. Also included in the images are the corresponding responses using the expressions proposed for structural stainless steel plates developed by Rasmussen [34] and included in EN 1993–1–4, Annex C [26]. It is clear that the proposed model provides a more accurate and representative prediction of the overall response in terms of shape and strain hardening behaviour as well as the yield and ultimate strength. On the other hand, it is clearly observed that the current material model given in EN 1993–1–4 [26] provides a reasonable but less accurate representation of the actual experimental stress-strain response for both austenitic and duplex stainless steel reinforcement. It is worth noting that the proposed curves end at $\varepsilon_{u,prop}$ as given in Eq. 16.

6. Conclusions

This paper presents a comprehensive study on the stress-strain stainless steel reinforcement. A large programme of tensile tests were conducted to obtain the stress-strain response for both austenitic and duplex stainless steel reinforcement. This is the first time that a dedicated programme of work was conducted on stainless steel reinforcement, as opposed to stainless steel plate, to ascertain the key properties required for analysis and design. A thorough review of the current material models developed for structural stainless steel elements is presented. The accuracy of these models for representing the stress-strain constitutive relationship of stainless steel reinforcement is assessed. Based on the results and analysis presented in this paper, a new material model with the key material parameters is proposed specifically for austenitic and duplex stainless steel reinforcement. It is shown that existing models, which were developed for stainless steel plate rather than reinforcing bars, are not capable of providing an accurate depiction of the full stress-strain response. The proposed model is validated in terms of the shape as well as strength, stiffness and strain characteristics, compared with experimental data. It is concluded that the proposed material models are capable of providing excellent predictions of the experimental response both for austenitic and duplex stainless steel reinforcing bars.

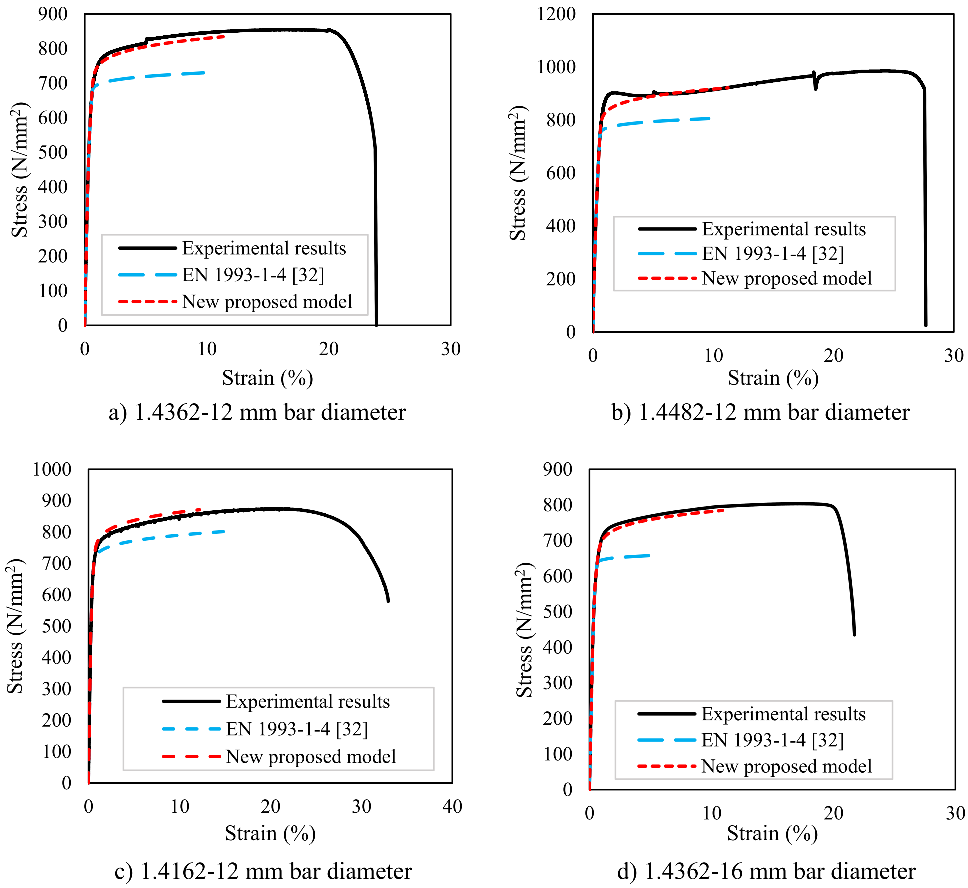

Fig. 13. Comparison of the proposed material model for duplex stainless steel reinforcement and the method currently included in EN 1993–1-4 [26] for structural stainless steel plate.

CRediT authorship contribution statement

Katherine Ann Cashell: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rabee Shamass:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Musab Rabi:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors wish to confirm that there are no known conflicts of interest associated with this research. We understand that the Corresponding Author is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author.

Data Availability

Data will be made available on request.

Acknowledgement

The authors would also like to thank the technician Paul Elsdon for his continuous support in the Laboratory and conducting the testing.

References

[1] M. Rabi, R. Shamass, K.A. Cashell, Structural performance of stainless steel reinforced concrete members: a review, Constr. Build. Mater. 325 (2022) 126673.
[2] C. Xu, M.L. Nehdi, M.A. Youssef, T. Wang, L.V. Zhang, Seismic performance of RC beam-column edge joints reinforced with austenite stainless steel, Eng. Struct. 232 (2021) 111824.
[3] M. Panagiotou, W. Trono, G. Jen, P. Kumar, C.P. Ostertag, Experimental seismic response of hybrid fiber-reinforced concrete bridge columns with novel longitudinal reinforcement detailing, J. Bridge Eng. 20 (7) (2015) 04014090.
[4] J. Ožbolt, G. Balabanić, M. Kušter, 3D Numerical modelling of steel corrosion in concrete structures, Corros. Sci. 53 (12) (2011) 4166–4177.
[5] M. Rabi, K.A. Cashell, R. Shamass, P. Desnerck, Bond behaviour of austenitic stainless steel reinforced concrete, Eng. Struct. 221 (2020) 111027.
[6] M. Rabi, K. Cashell, R. Shamass, Flexural analysis and design of stainless steel reinforced concrete beams, Eng. Struct. 198 (2019) 109432.
[7] O. Troconis de Rincón, J.C. Montenegro, R. Vera, A.M. Carvajal, R.M. De Gutiérrez, S. Del Vasto, E. Saborio, A. Torres-Acosta, J. Pérez-Quiroz, M. Martínez-Madrid, M.G. Lomeli-González, Reinforced concrete durability in marine environments DURACON project: long-term exposure, Corrosion 72 (6) (2016) 824–833.
[8] M.C. Alonso, F.J. Luna, M. Criado, Corrosion behavior of duplex stainless steel reinforcement in ternary binder concrete exposed to natural chloride penetration, Constr. Build. Mater. 199 (2019) 385–395.
[9] A. Fahim, A.E. Dean, M.D. Thomas, E.G. Moffatt, Corrosion resistance of chromium-steel and stainless steel reinforcement in concrete, Mater. Corros. 70 (2) (2019) 328–344.
[10] F. Lollini, M. Gastaldi, L. Bertolini, Performance parameters for the durability design of reinforced concrete structures with stainless steel reinforcement, Struct. Infrastruct. Eng. 14 (7) (2018) 833–842.
[11] L. Jinsong, G. Qian, L. Jing, F. Lin, Influence of calcium nitrite on electrochemical corrosion behavior of API X120 carbon steel and 316LN stainless steel reinforced concrete in marine environment, Int. J. Electrochem. Sci. 17 (22027) (2022) 2.
[12] J. Limbert, S. Afshan, M.M. Kashani, A.F. Robinson, Compressive stress–strain behaviour of stainless steel reinforcing bars with the effect of inelastic buckling, Eng. Struct. 237 (2021) 112098.
[13] L. Gardner, Y. Bu, P. Francis, N.R. Baddoo, K.A. Cashell, F. McCann, Elevated temperature material properties of stainless steel reinforcing bar, Constr. Build. Mater. 114 (2016) 977–997.
[14] I. Calderon-Uriszar-Aldaca, E. Briz, P. Larrinaga, H. Garcia, Bonding strength of stainless steel rebars in concretes exposed to marine environments, Constr. Build. Mater. 172 (2018) 125–133.
[15] Y. Zhou, Y. Ou, G.C. Lee, Bond-slip responses of stainless reinforcing bars in grouted ducts, Eng. Struct. 141 (2017) 651–665.
[16] M. Pauletta, N. Rovere, N. Randl, G. Russo, Bond-slip behavior between stainless steel rebars and concrete, Materials 13 (4) (2020) 979.
[17] M. Rabi, R. Shamass, K.A. Cashell, Experimental investigation on the flexural behaviour of stainless steel reinforced concrete beams, Struct. Infrastruct. Eng. 19 (12) (2023) 1847–1859.
[18] Q. Li, W. Guo, C. Liu, Y. Kuang, H. Geng, Experimental and theoretical studies on flexural performance of stainless steel reinforced concrete beams, Adv. Civ. Eng. (2020).
[19] E. Medina, J.M. Medina, A. Cobo, D.M. Bastidas, Evaluation of mechanical and structural behavior of austenitic and duplex stainless steel reinforcements, Constr. Build. Mater. 78 (2015) 1–7.
[20] S. Alih, A. Khelil, Behavior of inoxydable steel and their performance as reinforcement bars in concrete beam: experimental and nonlinear finite element analysis, Constr. Build. Mater. 37 (2012) 481–492.
[21] Khalifa, M., Heat of Hydration Thermal Performance and Flexural Capacity of Stainless-Steel Reinforced Concrete Sections, (Doctoral dissertation, The University of Western Ontario), (2019).
[22] Q. Li, Y. Kuang, W. Guo, Y. Zhang, Experimental research on mechanical performance of SSRC columns under eccentric compression, Appl. Sci. 10 (16) (2020) 5629.
[23] M. Rabi, K. Cashell, R. Shamass, Ultimate behaviour and serviceability analysis of stainless steel reinforced concrete beams, Eng. Struct. 248 (2021) 113259.
[24] Ramberg, W. and Osgood, W.R., 1943. Description of stress-strain curves by three parameters (No. NACA-TN-902).
[25] Hill, H.N., 1944. Determination of stress-strain relations from" offset" yield strength values. Aluminum Co of America Pittsburgh Pa.
[26] European Committee for Standardization, prEN 1993-1-4: Eurocode 3 - Design of steel structures - Part 1-4: General Rules - Supplementary Rules for Stainless Steel. Brussels, (2006).
[27] EN 1992-1-1., 'Eurocode 2: Design of concrete structures part 1-1: General rules and rules for buildings', European Committee for Standardization (CEN), (2004).
[28] BS 6744, Stainless steel bars for the reinforcement of concrete. Requirements and test methods, British Standards Institution (2016).
[29] I. Arrayago, E. Real, L. Gardner, Description of stress–strain curves for stainless steel alloys, Mater. Des. 87 (2015) 540–552.
[30] M. Rabi, K.A. Cashell, R. Shamass, Analysis of concrete beams reinforced with stainless steel, Proc. fib Symp. .: Concr. -Innov. Mater., Des. Struct. (2019) 690–697.
[31] Rabi, M., Analysis and design of stainless steel reinforced concrete structural elements (Doctoral dissertation, Brunel University London), (2020).
[32] X. Yun, Z. Wang, L. Gardner, Full-range stress–strain curves for aluminum alloys, J. Struct. Eng. 147 (6) (2021) 04021060.
[33] E. Mirambell, E. Real, On the calculation of deflections in structural stainless steel beams: an experimental and numerical investigation, J. Constr. Steel Res. 54 (1) (2000) 109–133.
[34] K.J. Rasmussen, Full-range stress–strain curves for stainless steel alloys, J. Constr. Steel Res. 59 (1) (2003) 47–61.
[35] L. Gardner, D.A. Nethercot, Experiments on stainless steel hollow sections—part 1: material and cross-sectional behaviour, J. Constr. Steel Res. 60 (9) (2004) 1291–1318.
[36] W.M. Quach, J.G. Teng, K.F. Chung, Three-stage full-range stress-strain model for stainless steels, J. Struct. Eng. 134 (9) (2008) 1518–1527.
[37] P. Hradil, A. Talja, E. Real, E. Mirambell, B. Rossi, Generalized multistage mechanical model for nonlinear metallic materials, Thin-walled Struct. 63 (2013) 63–69.
[38] EN 6892-1 (2016) 'Tensile testing of metallic materials part 1: Method of test at room temperature', European Committee for Standardization (CEN).
[39] Q. Li, W. Guo, C. Liu, Y. Kuang, H. Geng, Experimental and theoretical studies on flexural performance of stainless steel reinforced concrete beams, Adv. Civ. Eng. 2020 (2020) 1–13.
[40] Q. Li, Y. Cui, J. Wang, Basic mechanical properties of duplex stainless steel bars and experimental study of bonding between duplex stainless steel bars and concrete, Materials 14 (11) (2021) 2995.
[41] MATLAB and Statistics Toolbox Release 2019a. The MathWorks, Inc., Natick, Massachusetts, United States 2019.
[42] K.J.R. Rasmussen, G.J. Hancock, Design of cold-formed stainless steel tubular members. II: beams, J. Struct. Eng. 119 (8) (1993) 2368–2386.
[43] E. Real, I. Arrayago, E. Mirambell, R. Westeel, Comparative study of analytical expressions for the modelling of stainless steel behaviour, Thin-Walled Struct. 83 (2014) 2–11.
[44] I. Arrayago, E. Real, E. Mirambell, Constitutive equations for stainless steels: experimental tests and new proposal. In Research and Applications in Structural Engineering, Mechanics and Computation, CRC Press,, 2013, pp. 545–546.