**Compressive** **stress-strain behaviour of stainless steel reinforcing bars with the effect of inelastic buckling**

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# Abstract

The corrosion of steel reinforcing bars due to chloride ingress is the most common cause of premature deterioration of reinforced concrete structures. Stainless steel reinforcement in concrete is a promising solution to address these durability and sustainability issues as it is highly resistant to corrosion from chloride ions, and it does not rely on the high alkalinity of concrete or the presence of concrete cover for protection. Modelling and analysis of the nonlinear behaviour of reinforced concrete structural components relies heavily on the existence of constitutive material models to simulate the stress-strain response of the reinforcing bars and concrete accurately. In this paper, the stress-strain behaviour of stainless steel reinforcing bars with the effect of inelastic buckling is examined experimentally and numerically for the first time. Stainless steel reinforcing bars of 12 mm diameter with various slenderness ratios of austenitic EN 1.4301 and duplex EN 1.4362 grades are tested under tension and compression. A validated finite element model of reinforcing bar in compression is developed which is used to conduct parametric study. A new compressive stress-strain constitutive model for stainless steel reinforcing bars is proposed which is calibrated against the numerical simulation data.

**Keywords:** Constitutive modelling, Experimentation, Inelastic buckling, OpenSees modelling, Reinforcing bar, Stainless steel.

# 1. Introduction

Reinforced concrete (RC) structures are subjected to several sources of deterioration of steel reinforcement, concrete or both, which reduces their safety and serviceability and shorten their useful service lives. In particular, corrosion of reinforcing steel and other embedded metals is known as the leading cause of deterioration in reinforced concrete structures [1]. Corrosion affects the overall structural capacity in different ways; e.g. cracking, delamination and spalling of the concrete cover, reduction in strength (flexural, shear, etc.) and a reduction in ductility. The main existing durability measures for controlling reinforcement corrosion is through the concrete mix quality, concrete cover thickness and crack width control [1-2]. These measures only delay the corrosion initiation, and do not eliminate the vulnerability of RC structures to corrosion. Maintenance of corroded reinforced concrete infrastructure can involve substantial interruption to services with direct cost implications.

The use of maintenance-free materials such as stainless steel reinforcing bars in concrete, is an alternative solution towards achieving reinforced concrete infrastructure with a desired serviceability, strength and durability performance with little or no maintenance requirements. The exceptionally higher chloride corrosion initiation threshold for stainless steel reinforcement (8% chloride ions by cement weight) over carbon steel reinforcement (0.4% chloride ions by cement weight) means there is no need for existing protection measures such as the high alkalinity of concrete or the presence of thick concrete cover [3-4]. Stainless steel reinforcement also has superior corrosion resistance and higher strength and ductility in comparison with surface treated corrosion resistant steels, such as epoxy coated and galvanised reinforcing bars, commonly used in RC bridges [5]. Although the initial material cost of stainless steel reinforcement is higher than that of carbon steel reinforcement, the inherent corrosion resistance of the material as well as its higher strength and ductility allows longer-life design together with improved life-cycle environmental, social and economic costs.

The structural behaviour of stainless steel reinforced concrete structures has not been investigated in detail. A limited number of experimental and numerical studies on the nonlinear behaviour of stainless steel reinforced concrete structures exist in the literature [6-11]. The focus of the previous studies has mainly been on the performance of individual flexural elements [e.g. 6-9] and columns for seismic design [e.g. 10-11]. Medina et al. [6] studied the flexural behaviour of duplex (AISI 2304) stainless steel reinforced concrete beams by means of four-point bending tests. Alih et al. [7] carried out experimental and numerical investigations on austenitic (304LN) stainless steel reinforced concrete beams. Geromel et al. [8] conducted three-point bending tests on austenitic (AISI 316L) reinforced concrete beams to investigate their load carrying capacity and ductility. Rabi et al. [9] carried out a numerical investigation into the flexural behaviour of stainless steel reinforced concrete beams and extended the deformation based design method for steel-composite structures proposed by Gardner et al. [12] to stainless steel reinforced concrete members. Franchi et al. [10] conducted cyclic loading tests on columns reinforced with austenitic (AISI 304) bars. Melo et al. [11] carried out full-scale column tests on duplex (EN 1.4462) stainless steel reinforced concrete columns under monotonic and cyclic lateral loading conditions. In all the above mentioned experimental, numerical and analytical research studies, the higher ductility and strain hardening of stainless steel reinforcing bars compared with carbon steel reinforcing bars were shown to have beneficial effect on the structural response at member level.

All the previous experimental studies have investigated the influence of the different stress-strain behaviour of stainless steel reinforcing bars on the structural performance of RC members. However, there is currently no validated constitutive material model that can simulate the stress-strain relationship of stainless steel reinforcement under monotonic and cyclic loadings. In the existing specifications, BS 6744:2016 [13] and TR51 Guidance on the use of stainless steel reinforcement [14], a simple monotonic tensile stress-strain relationship using the Ramberg-Osgood model is the only one available. This is a significant obstruction for numerical modelling of RC structures subjected to repeated static and dynamic loadings (e.g. earthquake). Therefore, an advanced constitutive material model to describe the nonlinear stress-strain behaviour of stainless steel reinforcing bars, subjected to monotonic tension, compression and cyclic loadings including fatigue life assessment is required.

In this paper, the tensile and compressive behaviour of stainless steel reinforcing bars is investigated. Stainless steel is known to exhibits a distinctly different stress-strain behaviour to carbon steel. It has a highly nonlinear stress-strain response with no clearly defined yield point and substantial strain hardening [15]. Previous research [16] showed that elastic modulus, yield stress, and hardening modulus significantly affect the inelastic buckling and post-buckling behaviour of carbon steel reinforcing bars. Therefore, the different stress-strain characteristics of stainless steel are expected to result in different compressive stress-strain response. Hence, the compressive stress-strain behaviour of stainless steel reinforcing bars needs to be investigated to (1) develop a constitutive model capable of replicating its behaviour for numerical modelling analysis and (2) to determine the critical buckling length to bar diameter (L/D) ratio required for the design of horizontal tie spacing in new columns.

The results of the experimental investigation and numerical modelling to characterise the material response of stainless steel reinforcing bars under monotonic tensile and compressive loading conditions including the effect of inelastic buckling are presented. Reinforcing bars from two stainless steel grades, austenitic EN 1.4301 and duplex EN 1.4362, were tested. The open-source finite element (FE) analysis platform OpenSees [17] was used to simulate the nonlinear response of individual stainless steel reinforcing bars subjected to monotonic compressive loading. The FE models were first validated against the measured test data and subsequently used to perform parametric studies where the effects of key parameters including (i) the bar length-to-diameter ratio, (ii) the yield stress and (iii) the level of strain hardening of the material were investigated. A new compressive stress-strain constitutive model for stainless steel reinforcing bars is proposed which is shown to replicate the response with good degree of predictive accuracy.

# 2. Experimental investigation

## 2.1 Overview

A laboratory testing programme comprising monotonic tensile and compressive tests was carried out to investigate the nonlinear stress-strain behaviour of stainless steel reinforcing bars. The tests were conducted in the Testing and Structures Research Laboratory (TSRL) at the University of Southampton. All tests were performed in an Instron 8802 100kN servo-hydraulic testing machine. The tested reinforcing bars were 12 mm diameter ribbed bars of austenitic EN 1.4301 and duplex EN 1.4362 stainless steel grades. The chemical compositions of the tested stainless steel reinforcing bars, as provided by the mill certificates, are presented in Table 1.

## 2.2 Experimental testing procedures

Monotonic tensile tests were performed to measure the basic tensile stress-strain response of the stainless steel reinforcing bars. Each coupon had an overall length of 220 mm, with a parallel length of 120 mm and 50 mm grip length at either ends of the rebar specimen. Standard gauge lengths of Lg0 = 5.65, where A0 is the original cross-sectional area of the rebar, were marked on the parallel length of the specimen for the determination of the plastic strain at fracture. Displacement control was used to drive the testing machine at a rate of 0.05 mm/s, in accordance with EN ISO 6892-2016 [18], until fracture. A clip-on extensometer was used to measure the strain over the specified 50 mm central gauge length. Two repeated tensile tests were performed for each stainless steel grade. Figure 1(a) shows the adopted test set-up and the instrumentation used for the monotonic tensile tests.

Monotonic compressive tests were carried out on the austenitic and duplex stainless steel reinforcing bars with different effective lengths. The slenderness ratio, known as the L/D ratio, where L is the effective length (parallel length) and D is the diameter, were 10, 12 and 15. A range of L/D ratios are selected to investigate the inelastic buckling behaviour of stainless steel reinforcing bars which can be used in the design RC components. The specimens were gripped at both ends over a distance of 50 mm. The machine was set to displacement control with a constant rate of 0.05 mm/s [18] and was stopped at a maximum displacement of 0.08L for all the specimens. Two repeated compressive tests were performed for each stainless steel grade and each L/D ratio, giving a total of 12 monotonic compressive tests. Strains were measured by means of imaging technique using a Manta G-504B camera, with a Nikon AF 50mm f/1.8D lens, to film the specimen at a frame rate of 2Hz. The displacement between two spots marked at the ends of the specimens were tracked during the test. An open source image processing software, Fiji-ImageJ [19], was used with the plugin TrackMate [20] to analyse the displacements of each specimen. The average compressive strains were calculated as the measured displacement divided by the specimen length L. Figure 1 (b) shows the adopted test set-up and the instrumentation used for the monotonic compressive tests.

## 2.3 Experimental results and discussions

### 2.3.1 Monotonic tensile test results

Figures 2 shows the measured tensile stress-strain behaviour of austenitic EN 1.4301 and duplex EN 1.4362 stainless steel grades over the (a) small-strain and (b) full-strain ranges. The tensile stress-strain response of 12 mm diameter grade 500C carbon steel rebar measured in [21] is also depicted in Figure 2 for comparison purposes. The key measured tensile material properties of the stainless steel reinforcing bars are presented in Table 2, where E is the Young’s modulus, f0.2 is the 0.2% proof stress, fu is the ultimate tensile stress, εu is the strain at ultimate tensile stress and εf,pl is the plastic strain at fracture. The two stage Ramberg-Osgood material model [15, 22] as presented in Equations 1 and 2 is commonly employed to represent the nonlinear stress-strain behaviour of stainless steel materials. Equations (1) and (2) were fitted to the measured tensile stress-strain response curves following the method described in [23] and the obtained strain hardening exponents n and n'0.2,u are reported in Table 2.

|  |  |
| --- | --- |
| For |  |
|  | (1) |
| For |  |
|  | (2) |

where, ε and σ are the engineering strain and stress, respectively, E0.2 is the tangent modulus at f0.2, εt,0.2 is the total strain at 0.2% proof stress and all other parameters are as previously defined.

As shown in Figures 2, the material behaviour of stainless steel is fundamentally different from that of carbon steel. The response of stainless steel reinforcing bars is characterised by a rounded stress-strain behaviour with no sharply defined yield point, as shown in Figure 2(a) for the tested austenitic and duplex grades, and a high ultimate-to-yield strength ratio and high ductility, particularly for the austenitic grade, as shown in Figure 2(b). These differences in the material stress-strain response have a direct influence on the composite behaviour and failure modes of stainless steel reinforced concrete structural components.

### 2.3.2 Monotonic compressive test results

Inelastic buckling of longitudinal reinforcing bars is the most common flexural failure mode in reinforced concrete columns. The compressive stress-strain response of the stainless steel reinforcing bars including the effect of inelastic buckling for varying L/D ratios were measured. The measured compressive stress-strain response curves for reinforcing bars with L/D = 10, 12 and 15 are shown in Figures 3 for the EN 1.4301 and EN 1.4362 stainless steel grades. Figure 4 shows the failure modes of the buckled stainless steel reinforcing bars. For all tested reinforcing bars, the compressive stress-strain response is similar to the tensile stress-strain curve up to a maximum compressive stress, beyond which the rebar undergoes inelastic buckling and the responses begin to deviate. The specimens undergo buckling at increasingly lower peak compressive stresses with increasing L/D ratio. Also, reinforcing bars with higher slenderness ratios i.e. larger L/D ratios exhibit a more pronounced post-peak stress softening response.

Figures 5 compares the compressive stress-strain responses of the austenitic EN 1.4301 and duplex EN 1.4362 stainless steel (SS) reinforcing bars with those of carbon steel (CS) reinforcing bars measured in [21]. Both stainless steels and carbon steel bars show similar trend of behaviour. However, the drop in the peak compressive stress with increasing L/D ratio for the carbon steel bars is significantly smaller than those observed for the stainless steel bars. This is due to the larger, as well as the earlier onset of lateral displacements of the stainless steel bars, which increase for bars with higher L/D ratios. This gives rise to a higher proportion of second order bending moments which results in a more substantial reduction in the peak compressive stresses. The stainless steel reinforcing bars also exhibit a lower degree of post-peak stress softening compared with their carbon steel counterparts, which is attributed to the substantially higher level of strain hardening exhibited by the stainless steel reinforcing bars as shown in Figure 2.

# 3. Numerical modelling and parametric study

## 3.1 Model development and validation

The open-source finite element (FE) analysis platform OpenSees [17] was used to simulate the nonlinear response of individual stainless steel reinforcing bars subjected to monotonic compressive loading. The force-based distributed plasticity beam-column (FBBC) element, available in OpenSees, was used in the two-dimensional (2D) nonlinear rebar models. The reinforcing bar sections were simulated by fibre sections to which the material properties were assigned. Rotational and displacement boundary conditions were applied at the reinforcing bar ends to mimic those of the experimental conditions. All degrees of freedom apart from the longitudinal translation at the loaded end were restrained at both ends of the models. Global geometric imperfections in the form of a half-sine wave and of amplitude equal to L/1000, where L is rebar length, were assigned to the models. The Corotational Transformation [17] command in OpenSees was used to model the geometric nonlinearities. A mesh sensitivity analysis was performed to determine the mesh sizes for the fibre sections and the FBBC elements. A fibre section mesh comprising 20 fibres in the radial direction and 50 fibres in the circumferential direction was employed. The FBBC elements were 12 mm long and had 5 Gauss-Lobatto integration points along the length of each element. Figure 6 presents a schematic representation of the reinforcing bar models.

The Giuffre-Menegotto-Pinto (GMP) material model [24,25\*] implemented in OpenSees material library as the Steel02 material model was employed to simulate the uniaxial stress-strain response of the stainless steel reinforcing bars. This model assumes a bilinear response envelope, with initial slope E and hardening slope Eh, and a smooth transition curve, of radius R0, between them as shown schematically in Figure 7. The Steel02 material model was first fitted to the measured tensile stress-strain curves of the reinforcing bars up to 2% strain, as shown in Figure 8, and the calibrated model parameters, presented in Table 3, were subsequently employed in the numerical models. In Table 3, Eis the Young’s modulus, fy is the yield stress, b is the post-yield strain-hardening ratio, R0 is the initial curvature between elastic and post-yield slope, cR1 and cR2 are the curvature variation parameters of Bauschinger curve after each strain reversal, a1 and a2 are the isotropic hardening parameters defining stress shift in compression and a3 and a4 are the isotropic hardening parameters defining stress shift in tension. The recommended default values for cR1 and cR2 and a1, a2, a3 and a4 were adopted as the monotonic envelope needed to be modelled only.

Figure 9 compares the compressive stress-strain responses of the reinforcing bars with different L/D ratios from the experiments and the OpenSees FE models for the EN 1.4301 and EN 1.4362 stainless steels. The comparisons show that the numerical model is capable of accurately simulating the compressive response of the stainless steel reinforcing bars undergoing inelastic buckling and can replicate their initial stiffness, peak compressive stress and post-peak softening characteristics with a high degree of predictive accuracy.

## Parametric study

Using the validated FE modelling procedures, parametric studies were undertaken to investigate the response of stainless steel reinforcing bars over a range of key behavioural parameters and to generate the performance data required for the development of the compressive stress-strain constitutive model described in Section 4. The investigated parameters included (1) the bar length-to-diameter L/D ratio, (2) the yield stress fy and (3) the level of strain hardening of the material as measured by the b parameter in the Steel02 material model.

## 3.2.1 Effect of L/D ratio

The buckling response of stainless steel reinforcing bars with varying slenderness ratio, L/D = 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28 and 30 were investigated. The bar diameter was set to 12 mm and the tensile stress-strain response pertaining to the austenitic EN 1.4301 and duplex EN 1.4362 grades of the validation models were adopted. Figure 10 shows the parametric stress-strain curves for the different L/D ratios. For both stainless steel grades, as the slenderness ratio increases, the peak compressive stress reached reduces and the post-yield buckling slope becomes increasingly steeper.

## 3.2.2 Effect of yield stress

The effect of yield stress on the compressive stress-strain response of the stainless steel reinforcing bars was investigated by varying the yield stress fy of the Steel02 material model. The yield stress was varied between 300 and 800 MPa, at 100 MPa intervals, for each slenderness ratio listed in Section 3.2.1 for both stainless steel grades. All other material properties were kept identical to those of the validation models. Figure 11 shows the example stress-strain responses of the EN 1.4301 and EN 1.4362 reinforcing bars with varying yield stresses for L/D = 10, 20, and 30. As expected, for a fixed L/D ratio, the pre-buckling responses show higher peak compressive stresses for higher fy values. However, the post-buckling responses exhibit a higher degree of softening and more noticeable pinching effect with increasing fy values, in particular for bars with high L/D ratios.

## 3.2.3 Effect of strain hardening

Stainless steel exhibits a substantially higher degree of strain hardening than carbon steel as illustrated in the measured tensile stress-strain curves presented in Figure 2. The effect of the degree of strain hardening on the inelastic buckling response of stainless steel reinforcing bars was investigated by varying the strain hardening parameter b of the Steel02 material model while maintaining all other material parameters constant as those of the validation models. The analysis was performed for reinforcing bars with varying L/D ratios, previously listed in Section 3.2.1, for both stainless steel grades. The strain hardening ratio b was varied from 0.005 (low degree of strain hardening) to 0.040 (high degree of strain hardening), with 0.005 intervals. Figure 12 shows the example stress-strain responses of the EN 1.4301 and EN 1.4362 reinforcing bars with varying strain hardening for L/D = 10, 20, and 30. As expected, the pre-buckling responses are not influenced by the strain hardening of the material with the peak compressive stress only being marginally higher for higher strain hardening levels for the case of the low L/D ratios. The post-yield inelastic buckling response is however influenced by the degree of strain hardening, whereby reinforcing bars with higher levels of strain hardening show a lower strength loss at large strain demand. This is more pronounced for the austenitic (EN 1.4301) bars than the duplex (EN 1.4362) bars, as they have a comparatively higher degree of strain hardening as shown in Figure 2. As the slenderness ratio L/D increases, the strain hardening level has a diminishing effect on the inelastic post-buckling response of the bars.

# 4. Material model development

Compressive stress-strain models for carbon steel reinforcing bars have been proposed by a number of researchers including those in [26-29]. The two most recently proposed compressive stress-strain constitutive models are by Dhakal and Maekawa [28] and Kashani et al. [29]; an overview of these models is given in this section. The development and validation of a new constitutive model for stainless steel reinforcing bars is presented.

## 4.1 Dhakal and Maekawa and Kashani et al. models

Dhakal and Maekawa [28] carried out a numerical modelling investigation using the fibre technique to study the inelastic buckling response of carbon steel reinforcing bars. It was found that the compressive behaviour of reinforcing bars is governed by the square root of the yield stress fy and the geometric slenderness ratio L/D. An analytical relationship for the compressive stress-strain response including the effect of inelastic buckling in terms of the non-dimensional slenderness ratio (where fy is in MPa) was proposed on the basis of results of their numerical parametric investigation. The model consists of a linear elastic response up to the yield (or peak) compressive stress followed by a three-stage post-yield buckling response. The post-yield buckling branch includes a linear stage from the yield point to a defined intermediate point followed by a linear portion with a constant negative stiffness equal to 0.02E up to the point where the compressive stress reaches a value of 0.2fy, beyond which a constant stress of 0.2fy is assumed. Eqs (3)-(6) describe the different stages of the proposed model in the adopted normalised stress σn (σ/fy) and normalised strain εn (ε/εy) form, where σ and ε are the current stress and strain, respectively and fy and εy are the yield stress and yield strain, respectively. A schematic representation of this model is shown in Figure 13. In Eqs (4-6), and are the normalised stress and strain of the specified intermediate point which are given by Eqs (7) and (8), where is the normalised tensile envelope stress corresponding to and α = 0.75 for reinforcement with elastic-plastic behaviour and α = 1.0 for reinforcement with linear hardening behaviour.

|  |  |
| --- | --- |
|  | (3) |
|  | (4) |
|  | (5) |
|  | (6) |
|  | (7) |
|  | (8) |

Kashani et al. [29] studied the compression response of uncorroded and corroded carbon steel reinforcing bars and proposed an analytical model to represent their buckling behaviour. The model assumes linear elastic behaviour up to the yield (or peak) compressive stress as in Dhakal and Maekawa’s [28] model, but employs an exponential function to describe the post-yield buckling response of reinforcing bars with 8 ≤ L/D ≤ 30 as given by Eq. (9) and illustrated schematically in Figure 14. In Eq. (9), and are stress and strain, respectively, E is the elastic Young’s modulus, is the asymptotic lower stress limit of the post-buckling curve, fy is the yield stress, is the yield strain, is the initial tangent of the post-buckling response curve, is the rate of change of the tangent and is the plastic strain i.e. . Expressions for the , and parameters as function of the yield stress fy and the geometric slenderness ratio L/D of the reinforcing bar given by Eqs (10)-(12), respectively were proposed. These were derived by model calibration against numerically generated buckling response curves for reinforcing bars with different L/D (8-30) and fy (100-600 MPa) values. In Eqs (10) and (11), (where fy is in MPa) is the non-dimensional slenderness ratio of the reinforcing bar as was adopted in Dhakal and Maekawa’s model [28]. Validation of the proposed model against the test data of individual reinforcing bars showed that the model can accurately predict the post-yield buckling response of carbon steel reinforcing bars [29].

|  |  |  |
| --- | --- | --- |
|  | | (9) |
|  | |
|  |  | (10) |
|  |  | (11) |
|  |  | (12) |

## 4.2 Proposed model for stainless steel reinforcing bars

### 4.2.1 Model calibration

A modified version of the compressive stress-strain constitutive model proposed by Kashani et al. [29] as given by Eq (13) and illustrated in Figure 15, was developed for stainless steel reinforcing bars. Unlike in carbon steel reinforcing bars where the peak compressive stress was set equal to the yield stress for bars of varying length-to-diameter L/D ratios, for stainless steel reinforcing bars, the peak compressive stress was found to be a function of the L/D ratio as shown in Figure 10. Hence, to reflect this, the peak compressive stress σmax rather than the yield stress fy was used in the constitutive model. The results of the parametric study presented in Section 3.2 were used for the calibration of the model parameters , , and .

|  |  |
| --- | --- |
|  | (13) |
|  |

The analysis data related to the post-buckling branch of the compressive stress-strain responses of the modelled reinforcing bars (180 curves for each modelled stainless steel grade) were exported to MATLAB. Using the CFT (curve fitting toolbox) available in MATLAB, Eq. (13) was fitted to each post-buckling response curve. Using this approach, the parameters , and in Eq. (13) were optimised to provide the best fit to the simulated post-buckling response of the bars. The optimised model parameters (, and ) for each analysis case from the curve fitting procedure were stored and used to perform regression analysis to develop suitable predictive relationships in terms of the bar slenderness . A new definition of the non-dimensional bar slenderness as given in Eq. (14) is adopted which is in terms of the strain hardening slope Eh (= b × E), which was shown in Section 3.2.3 to be an important influencing parameter on the bar buckling behaviour. An additional advantage of using Eh rather that 100 (in MPa) in the definition is that the equation is no longer dependent on the unit of the yield stress fy.

|  |  |  |
| --- | --- | --- |
|  |  | (14) |

Figures 16 and 17 show the model parameters determined from the simulation data as well as the models resulting from the regression analyses and the correlation coefficients for the austenitic EN 1.4301 and duplex EN 1.4362 stainless steel reinforcing bars, respectively. The results of the curve fitting are presented in Eqs (15)-(18) and Eqs (19)-(22) for the austenitic EN 1.4301 and duplex EN 1.4362 stainless steel reinforcing bars. In Eqs (14), (18) and (22), fy is the tensile yield stress of the calibrated Steel02 material model, and all other parameters are as previously defined.

For austenitic (EN 1.4301) reinforcing bars:

|  |  |
| --- | --- |
|  | (15) |
|  | (16) |
|  | (17) |
| but ≤ fy | (18) |

For duplex (EN 1.4362) reinforcing bars:

|  |  |
| --- | --- |
|  | (19) |
|  | (20) |
|  | (21) |
| σmax = 1.17fy – 0.022fy (L/D) but ≤ fy | (22) |

### 4.3.2 Model validation

The proposed compressive stress-strain constitutive model was validated against the FE simulation data of the tested austenitic EN 1.4301 and duplex EN 1.4362 stainless steel reinforcing bars. The numerical stress-strain curves of the tested rebars were not included in the model calibration and were therefore adopted for the verification of the proposed model. Figure 18 shows a comparison between the proposed model and the numerical simulation data of the tested reinforcing bars. Table 4 presents the numerical comparison results in terms of the model-to-FE maximum stress ratio σmax,model/σmax,FE, the model-to-FE post-peak dissipated energy ratio Emodel/EFE and the % model error for the individual stress-strain curves together with their mean and coefficient of variation (COV) values. The mean and COV values for the maximum stress σmax are 1.058 and 0.027, respectively. This slight over-prediction can be explained by the highly nonlinear stress-strain response of stainless steel, in particular around the maximum stress region, which is not captured by the proposed model. The model post-peak dissipated energy was found to be lower, on average by 8%, than the FE post-peak dissipated energy, which in turn resulted a model error that varies from 4.57% to 12.99%. It should be noted that this error is smaller for reinforcing bars with more common larger L/D ratios, where the post-peak response is less influenced by the nonlinearity and the strain hardening characteristics of the material. Improvements to the post-peak buckling response branch of the model may be made by developing a nonlinear transition region between the initial linear elastic and the inelastic post-peak responses. Overall, the proposed model provides a simple and accurate relationship for the compressive stress-strain response of stainless steel reinforcing bars including the effect of inelastic buckling.

# 5. Conclusions

The stress-strain behaviour of stainless steel reinforcing bars with the effect of inelastic buckling was examined experimentally and numerically in this paper for the first time. The experimental investigation included monotonic tensile and compressive tests on reinforcing bars from austenitic EN 1.4301 and duplex EN 1.4362 stainless steel grades. In the numerical modelling study, performed in the open-source finite element (FE) analysis platform OpenSees, validated finite element models of individual stainless steel reinforcing bars subjected to monotonic compressive loading were developed, and subsequently used to conduct parametric studies. The effect of the bar length-to-diameter ratio, the yield stress and the level of strain hardening of the material were investigated. A new compressive stress-strain constitutive model for stainless steel reinforcing bars was developed using the performance data from the numerical simulation analyses. The proposed model was shown to simulate the response of stainless steel reinforcing bars with a good degree of accuracy. Future work will focus on incorporating the proposed compressive model into a more general cyclic response constitutive model, including the effect of fatigue degradation, required for the nonlinear analysis of RC structures with stainless steel reinforcement.

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| **Clip-on Extensometer**  **Test specimen** | **Test specimen**  **Camera** |
| 1. Tensile test set-up. | 1. Compressive test set-up. |
| Figure 1: Test set-up and instrumentation for tensile and compressive tests. | |

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| 1. Small-strain range |
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| 1. Full-strain range |
| Figure 2: Measured tensile stress-strain curves of EN 1.4301 and EN 1.4362 stainless steel reinforcing bars and comparison with 500C carbon steel reinforcing bar. |
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| 1. EN 1.4301 stainless steel |
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| 1. EN 1.4362 stainless steel |
| Figure 3: Compressive stress-strain response of stainless steel reinforcing bars with L/D = 10, 12 and 15 for (a) EN 1.4301 and (b) EN 1.4362. |

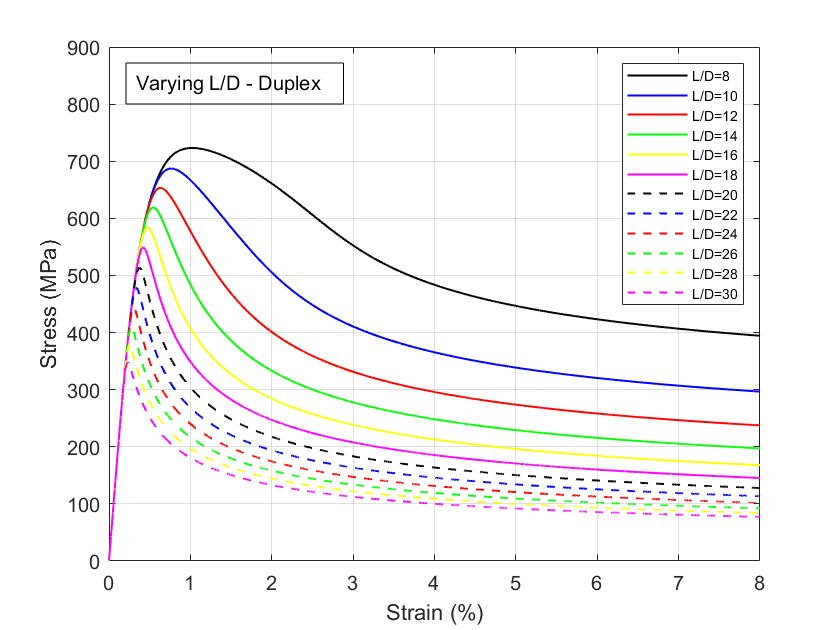
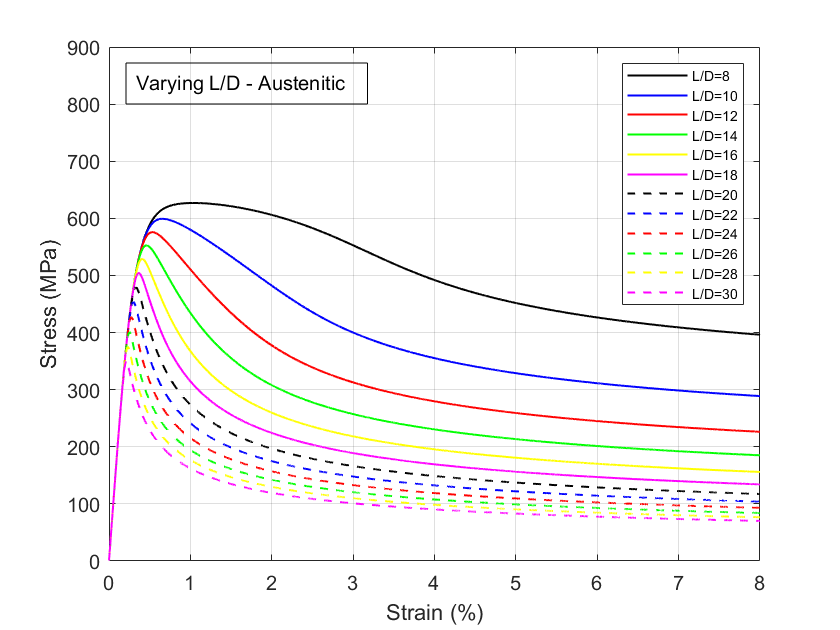
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| 1. EN 1.4301 stainless steel |
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| 1. EN 1.4362 stainless steel |
| Figure 4: Buckled shapes of (a) EN 1.4301 and (b) EN 1.4362 stainless steel reinforcing bars. |

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| 1. EN 1.4301 stainless steel |
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| 1. EN 1.4362 stainless steel |
| Figure 5: Comparison of the compressive stress-strain responses of (a) EN 1.4301 and (b) EN 1.4362 stainless steels with 500C carbon steel reinforcing bars. |
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| Figure 6: Schematic representation of the reinforcing bar OpenSees model. |

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| Figure 7: Schematic representation of the monotonic Steel02 material model and definition of key parameters. |

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| 1. EN 1.4301 stainless steel. | 1. EN 1.4362 stainless steel. |
| Figure 8: Calibration of the Steel02 material model against the measured tensile stress-strain curves for (a) EN 1.4301 and (b) EN 1.4362 stainless steels. | |

|  |  |
| --- | --- |
|  |  |
| 1. L/D = 10 (EN 1.4301) | 1. L/D = 12 (EN 1.4301) |
|  |  |
| 1. L/D = 15 (EN 1.4301) | 1. L/D = 10 (EN 1.4362) |
|  |  |
| 1. L/D = 12 (EN 1.4362) | 1. L/D = 15 (EN 1.4362) |
| Figure 9: Comparison between the OpenSees and the experimental compressive responses. | |



1. EN 1.4301 stainless steel (b) EN 1.4362 stainless steel

Figure 10: Parametric stress-strain curves for varying L/D ratios between 8-30, for (a) EN 1.4301 and (b) EN 1.4362 reinforcing bars.

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| --- | --- |
| A close up of a map  Description automatically generated | A close up of a map  Description automatically generated |
| 1. L/D = 10 (EN 1.4301) | 1. L/D = 20 (EN 1.4301) |
| A close up of text on a white background  Description automatically generated | A close up of a map  Description automatically generated |
| 1. L/D = 30 (EN 1.4301) | 1. L/D = 10 (EN 1.4362) |
| A close up of a map  Description automatically generated | A close up of a map  Description automatically generated |
| 1. L/D = 20 (EN 1.4362) | 1. L/D = 30 (EN 1.4362) |
| Figure 11: Parametric stress-strain curves for varying yield stress fy for (a)-(c) EN 1.4301 and (d)-(f) EN 1.4362 reinforcing bars, with L/D ratios of 10, 20 and 30. | |

|  |  |
| --- | --- |
| A close up of a map  Description automatically generated | A close up of a map  Description automatically generated |
| 1. L/D = 10 (EN 1.4301) | 1. L/D = 20 (EN 1.4301) |
| A screenshot of a cell phone  Description automatically generated | A close up of a map  Description automatically generated |
| 1. L/D = 30 (EN 1.4301) | 1. L/D = 10 (EN 1.4362) |
| A close up of a map  Description automatically generated | A screenshot of a cell phone  Description automatically generated |
| 1. L/D = 20 (EN 1.4362) | 1. L/D = 30 (EN 1.4362) |
| Figure 12: Parametric stress-strain curves for varying strain hardening parameter b for (a)-(c) EN 1.4301 and (d)-(f) EN 1.4362 reinforcing bars, with L/D ratios of 10, 20 and 30. | |

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| Figure 13: Schematic representation of the analytical model from Dhakal and Maekawa. [27] |

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| Figure 14: Schematic representation of the analytical model from Kashani et al. [28] |

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| Figure 15: Schematic representation of the proposed compressive stress-strain model for stainless steel reinforcing bars. |

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| 1. ρ1 (EN 1.4301) | 1. ρ2 (EN 1.4301) |
|  |  |
| 1. σ\* (EN 1.4301) | 1. σmax (EN 1.4301) |
| Figure 16: Calibration of model parameters for austenitic EN 1.4301 stainless steel reinforcing bars. | |

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| --- | --- |
|  |  |
| 1. ρ1 (EN 1.4362) | 1. ρ2 (EN 1.4362) |
|  |  |
| 1. σ\* (EN 1.4362) | 1. σmax (EN 1.4362) |
| Figure 17: Calibration of model parameters for duplex EN 1.4362 stainless steel reinforcing bars. | |

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| --- | --- |
|  |  |
| 1. L/D = 10 (EN 1.4301) | 1. L/D = 12 (EN 1.4301) |
|  |  |
| 1. L/D = 15 (EN 1.4301) | 1. L/D = 10 (EN 1.4362) |
|  |  |
| 1. L/D = 12 (EN 1.4362) | 1. L/D = 15 (EN 1.4362) |
| Figure 18: Verification of the proposed compressive stress-strain constitutive model against the experimental data. | |

Table 1: Chemical composition of the tested stainless steel reinforcing bars in (%).

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Grade | C | Si | Mn | Cr | Mo | Cu | Ni | P | S | N |
| Austenitic EN 1.4301 | 0.019 | 0.41 | 1.90 | 18.42 | - | - | 8.16 | 0.03 | 0.001 | 0.22 |
| Duplex EN 1.4362 | 0.018 | 0.56 | 1.30 | 23.47 | 0.35 | 0.49 | 4.32 | 0.03 | 0.002 | 0.09 |

Table 2: Summary of key tensile material properties.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Specimen | E  (N/mm2) | f0.2  (N/mm2) | fu  (N/mm2) | εu  (%) | εf,pl  (%) | n | n'0.2,u |
| EN 1.4301-1 | 200000 | 572 | 824 | 26.3 | - | 4.83 | 4.32 |
| EN 1.4301-2 | 192000 | 554 | 827 | 28.2 | 31.7 | 4.75 | 4.91 |
| EN 1.4362-1 | 185000 | 634 | 838 | 15.5 | - | 3.82 | 9.40 |
| EN 1.4362-2 | 184000 | 612 | 828 | 13.7 | 26.7 | 3.95 | 9.22 |

Table 3: The calibrated Steel02 material model parameters.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stainless steel grade | E  (N/mm2) | fy  (N/mm2) | b | R0 | cR1 | cR2 | a1 | a2 | a3 | a4 |
| EN 1.4301 | 192000 | 630 | 0.025 | 3.0 | 0.925 | 0.15 | 0 | 1 | 0 | 1 |
| EN 1.4362 | 184000 | 750 | 0.025 | 2.6 | 0.925 | 0.15 | 0 | 1 | 0 | 1 |

Table 4: Ratios of maximum stress and post-buckling dissipated energy from proposed model and FE simulation of the tested stainless steel reinforcing bars

|  |  |  |  |
| --- | --- | --- | --- |
| Reinforcing bar |  |  | (%) |
| L/D = 10 (EN 1.4301) | 1.026 | 0.903 | 9.75 |
| L/D = 12 (EN 1.4301) | 1.029 | 0.921 | 7.90 |
| L/D = 15 (EN 1.4301) | 1.083 | 0.954 | 4.57 |
| L/D = 10 (EN 1.4362) | 1.087 | 0.870 | 12.99 |
| L/D = 12 (EN 1.4362) | 1.041 | 0.925 | 7.54 |
| L/D = 15 (EN 1.4362) | 1.080 | 0.944 | 5.63 |
| Mean | 1.058 | 0.920 | 8.06 |
| COV | 0.027 | 0.033 | 0.37 |