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Evaluation of mechanical and structural behavior of austenitic and duplex stainless steel reinforcements

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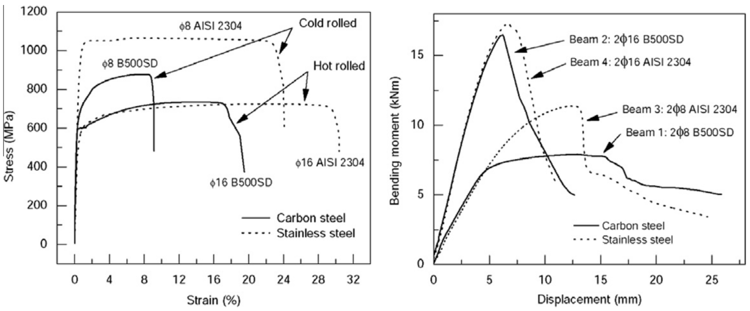
HIGHLIGHTS

- Stainless steel (SS) reinforcements offer high ductility performance to fracture.
- SS reinforced concrete provides long-lasting constructions and buildings.
- SS reinforcements show higher ductility than carbon steel (CS) when hot rolled.
- SS reinforcements reach a slightly lower modulus of elasticity than CS.

GRAPHICAL ABSTRACT



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ABSTRACT

The mechanical and structural behavior of three stainless steel (SS) reinforcing bars (austenitic AISI 304, duplex AISI 2304 and new lean duplex AISI 2001) have been studied and compared with the conventional carbon steel (CS) B500SD. The study was conducted at rebar level, cross-section level and structural member level. The results demonstrate higher ductility performance for hot-rolled SS rebars than for CS, but lower ductility for cold-rolled SS rebars compared to CS. The experimental elastic modulus of SS rebars is lower than that of CS.

1. Introduction

Corrosion of carbon steel (CS) reinforcements is the main durability problem in conventional concrete structures and the most difficult to avoid in certain circumstances. Protection against corrosion is provided by the thickness and the impermeability of the concrete cover, as well as the self-regenerating thin passive oxide layer that is formed at the steel–concrete interphase due to the high alkalinity of concrete. The pH of Portland cement paste during the setting process reaches values ranging between 12.5 and 13.5 because of hydroxide formation.

Steel remains in a passive state until the pH drops to values lower than 11.4 [1], 11 [2] or 9.5 [3]. pH decreases are primarily due either to concrete carbonation (calcium-bearing phases are attacked by carbon dioxide from the air) or the presence of depassivating ions, especially chlorides [4]. The latter may come from salt fog in the case of structures close to the coast, from sea water if they are fully or partially submerged, or from de-icing salts in the case of road bridges in frost areas.

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The feature that distinguishes stainless steel (SS) reinforcements from CS rebars is their excellent resistance to corrosion, including that triggered by chloride ions. SS contains a minimum of 10.5% chromium [5], which forms a very thin self-regenerating chromium oxide layer that is resistant to atmospheric or electrochemical corrosion, as well as other alloys such as nickel, molybdenum, manganese, copper and nitrogen which confer additional features. A wide variety of SS alloys and types can be found for multiple applications.

Austenitic and duplex SS are the two types most commonly employed to manufacture reinforcing bars, although their high price, between 4 and 7 times that of CS [6], limits their use to structures in very aggressive environments or whose life is to be extended. Austenitic SS reinforcements were first used in 1941 at Progreso pier in Mexico [7] and their tolerance to chlorides is 5–10 times higher than that of CS [8]. Duplex SS reinforcements are currently more commonly used because their lower nickel content makes them more economical than austenitic SS, nickel being an expensive alloying element whose market price has suffered strong fluctuations since 2006. Duplex SS rebars also present greater resistance to corrosion by chloride pitting [9,10].

In recent years low-nickel duplex SS reinforcements, which compensate their lower nickel content with a higher manganese content, have appeared on the market. Low-nickel AISI 2001 and 2101 lean duplex SS are cheaper than 2205 and 2304 duplex SS, but all four present similar resistance to chloride corrosion [11,12]. SS rebars offer scope for relaxing concrete durability measures originally designed to protect CS, such as minimum covers [13] and maximum design crack widths [14]. Furthermore, several studies have shown that the combined use of SS and CS rebars does not increase the risk of reinforcement corrosion compared to the use of CS alone, even when the bars are in direct electrical contact [15,16]. This means that the use of SS reinforcements can be restricted to the most exposed structural members in order to lengthen the design service life of newly built structures while reducing their economic impact on the total cost of the concrete structure.

Other interesting applications when cost is not decisive include the rehabilitation of concrete structures affected by corrosion, replacing corroded CS reinforcements or providing a new replacement reinforcement concrete cover [17], and the reinforcement of brick or stone walls on bridges or historic buildings such as churches, cathedrals, etc., placing the highly corrosion-resistant rebars in mortar joints with a minimal cover [18]. In the case of historic buildings – many of which are located in earthquake zones where the structural layout of the walls is adapted to seismic conditions as a result of long experience [19] – the good ductility properties of SS reinforcements are an added advantage.

However, the use of SS reinforcements is still rare and their mechanical and structural behavior is not known in detail, as it is for CS. The present work has studied the performance of SS rebars, a cross-section of a concrete beam and a structural member in order to assess the mechanical and structural behavior of three types of SS reinforcements, one austenitic and two duplex, in comparison with traditional B500SD carbon steel (Spanish EHE-08 standard [20] high ductility and creep-resistant corrugated steel with a yield strength of $f_y \geqslant 500$ MPa, "Grade C" according to Eurocode 2 (EC2) [21]).

2. Experimental procedure

2.1. Study at bar level

The study of the mechanical behavior and ductility of SS reinforcements by analysis of austenitic type AISI 304 (EN 1.4301) and duplex AISI 2304 (EN 1.4362) and 2001 (EN 1.4482) SS together with B500SD carbon steel as a reference has firstly been studied at bar level. These steels have been tested to tensile strength in agreement with European standards EN 10002-1 [22] and ISO 15630-1 [23] using a MIB 60/AM Ibertest machine. The tests were performed on specimens with a nominal diameter of 8 mm in the case of cold-rolled AISI 304, AISI 2304 and B500SD steels, and 16 and 20 mm for hot-rolled steels. Chemical analysis of the studied reinforcements was conducted by inductively coupled plasma emission spectroscopy. Composition results are shown in Table 1.

Based on the results obtained in the tensile tests, ductility parameters have been calculated for each of the four steels according to the following criteria:

(a) The criteria established in several European regulations; specifically Model Code 2010 (MC 2010) [24], and Eurocode 2 (EC2) [21], using the ultimate tensile strength to yield strength ratio f_t/f_y (hardening ratio) and the ultimate strain for the maximum (ultimate) strength ε_u.

(b) The strength requirements and ductility set out in American Standard ASTM A615 [25] for grade 60 steels in the case of calculation for earthquakes.

(c) The concept of equivalent steel according to the p parameter of Cosenza (Eq. (1)), the area A_{nom} defined by Creazza (Eq. (2)) and the toughness index I_d of Ortega (Eq. (3)) [2,26]:

$$p = \left(\frac{f_t}{f_y} - 1\right)^{0.9} (\varepsilon_u + 3\varepsilon_{sh})^{0.75} \tag{1}$$

$$A_{nom} = \frac{2}{3}(\varepsilon_u - \varepsilon_y)(f_t - f_y) \tag{2}$$

$$I_d = \left(1 + \frac{f_t}{f_y}\right)\left(\frac{\varepsilon_u}{\varepsilon_y} - 1\right) \tag{3}$$

where f_t is the ultimate tensile strength, f_y is the yield strength, ε_y is the strain at yield strength, ε_u is the ultimate strain, ε_{sh} is the strain at the end of the yield plateau corresponding to initial strain hardening (for hot-rolled CS reinforcements) and ε_y is the strain at yield strength.

(d) The *Comité Euro-International du Béton* proposal [2] for a new classification of steel ductility based on the formulation of Cosenza, which establishes the following limits for high-ductility or *S*-class steels:

$$\left(\frac{f_t}{f_y} - 1\right)_k \geq 0.13 \quad \text{and} \quad \varepsilon_u \geq 9\% \tag{4}$$

$$\left(\frac{f_t}{f_y} - 1\right)_k \geq 0.15 \quad \text{and} \quad \varepsilon_u \geq 6\% \tag{5}$$

$$\left(\frac{f_t}{f_y} - 1\right)_k \geq 0.17 \quad \text{and} \quad \varepsilon_u \geq 5\% \tag{6}$$

2.2. Study at section level

For the study at section level, moment–curvature M–χ diagrams of two standard beam sections have been produced by iteration of up to seven possible points. The beams were a 50 × 30 cm flat beam and a 30 × 50 cm downstand beam reinforced with different amounts of CS and duplex SS rebars as detailed in Table 2. The duplex SS type was selected because it is the most widely used [27] and exhibits similar mechanical characteristics to the austenitic type, as shown in the tensile test results obtained in the present study.

For calculation purposes, the idealized strength–strain diagrams represented in Fig. 1 have been chosen, taking the parabola-rectangle diagram for concrete compression and the bilinear diagram with a horizontal upper branch for CS and SS rebars. Both diagrams have been prepared according to Eurocode 2 (EC2). A maxi-

Table 1
Chemical composition of tested steels (weight%, balance Fe).

Steel	C	Si	Mn	P	S	Cr	Ni	Cu	N	Mo
AISI 304	0.02	0.28	1.41	0.034	0.023	18.07	7.93	0.33	0.05	0.22
AISI 2304	0.02	0.35	0.81	0.029	0.010	22.75	4.32	0.31	0.14	0.29
AISI 2001	0.03	0.65	4.19	0.023	0.010	20.07	1.78	0.08	0.13	0.22
B500SD	0.20	0.22	0.72	<0.01	0.022	0.13	0.13	0.18	–	–