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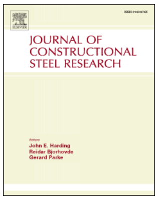

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Behaviour of stainless steel press-braked channel sections under compression

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ABSTRACT

This paper describes an experimental and numerical investigation of stainless steel material response and behaviour of press-braked channel sections under pure axial compression. A material test programme that covers austenitic stainless steel EN 1.4301 was carried out to study the nonlinear stress–strain relationship and changes of basic mechanical properties due to the press-braking processes. The key experimental results were used to estimate the appropriateness of existing analytical material models and to determinate strain-hardening exponents. The validation of recently proposed models for predicting the strength enhancements in cold-formed sections was also performed. Additionally, corresponding Finite Element (FE) models were built for flat and corner coupons to match the tensile test results and to establish the parameters of a ductile damage model in Abaqus. The susceptibility to local buckling of the channel section was determined by stub column tests. The FE model, calibrated and validated against the experiments, was used to perform a parametric study over a wide range of section slenderness. This allowed the quantitative assessments of design procedures stated in Eurocode 3 and American Specifications, and the Continuous Strength Method (CSM). The comparisons between generated data and predicted strengths reveal the conservatism of the Eurocode 3 design method for both non-slender and slender channels. In contrast, the CSM reflects significantly better the nonlinear buckling behaviour of non-slender channels. Although this method gives more accurate results comparing to effective with method employed in Eurocode 3, the slight unsafe predictions were found for slender channels in the intermediate cross-section slenderness.

1. Introduction

Stainless steel belongs to the group of contemporary, sustainable and renewable structural materials. It is characterized by high corrosion resistance, superior appearance, nonlinear behaviour, pronounced ductility and material strengthening effects due to cold-working, retention of mechanical properties at high temperatures, good toughness at low temperatures, harmlessness to the natural environment and good recycling potential. Its application in civil engineering has become synonymous with luxurious and architecturally attractive structures, while its utilization is still limited in conventional structures. The reason for this is a very high cost of stainless steel and, sometimes, the lack of recognition of its long-term benefits by design engineers. Numerous comparative studies on the effects of basic material choice on a structure's life-cycle, including initial and maintenance costs, reflected in corrosion protection, fire protection and restoration activities, demonstrate that stainless steel has an economic advantages in a wide variety of structural applications. Responding to market demand and the permanent improvement of the manufacturing process, the metalworking industry initiated the production of new, low alloys of stainless steel: the ferritic and lean duplex grades, which contain $<1.5\%$ of nickel and can simultaneously ensure primary properties of stainless steel with an economically competitive price [1,2,3,4]. Changing the views within civil engineering and following a global transition to sustainable development, reductions in environmental impact as well as the availability of a wide range of stainless steel products, together with extension of current design codes, represent crucial elements for increasing the use of structural stainless steel.

Apart from the numerous similarities in the design of stainless steel and carbon steel structural elements and connections, the differences in mechanical and thermal properties of these two materials require a modification of the carbon steel design rules for their implementation in stainless steel structural design.

The part of Eurocode 3 for design of stainless steel structural elements EN 1993-1-4 [5] is, to a great extent, harmonised with the basic Eurocode 3 for design of carbon steel structures EN 1993-1-1 [6], but the disparity in scope and content of these two standards is very considerable. The lack of experimental data in different design fields of

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stainless steel structures results in the fact that the current design provisions in EN 1993-1-4 [5] rely solely on assumed analogies with equivalent carbon steel structures. However, such an approach does not fully identify the specific performances of stainless steel that are strongly associated with the overall behaviour of a structural element. In order to complete but also revise the existing regulations in the domain of stainless steel structural design, several research programmes were initiated in recent years. Providing new and reliable data for a better understanding of stainless steel structural behaviour, some of them resulted in innovative design methods and recommendations [7].

Unlike carbon steel, stainless steel exhibits a nonlinear response with gradual yielding. A precise mathematical description of the stainless steel stress–strain relationship is essential for use in research that does not include an experimental part. Various analytical material models exist in literature [8,9,10,11,12] and all of them are based on the Ramberg–Osgood [13] and modified Hill models [14]. Material properties of stainless steel considerably change through the cold-working process. As a response to plastic deformation, the material exhibits a hardening effect that is manifested through an increase in the yield and tensile strength, but also in a decrease in ductility and in the formation of residual stresses. Although stainless steel is widely used in the construction industry as a cold-formed product, the influence of the cold-working process on the improvement of mechanical properties is not analytically covered in EN 1993-1-4 [5]. It is clear that for a material with a high initial cost, full exploitation of its properties in structural design is essential. Several predictive models for determining the strength enhancements of stainless steel were developed in the previous period [15,16,17,18,19]. In case of compressed stainless steel elements, the majority of experimental programmes included cold-formed hollow sections, while experimental data on different types of open cross-sections are still limited. Table 1 provides a summary of the gathered database for stainless steel stub column tests under axial compression. The collected database covers a wide range of structural section types, structural materials and numbers of tests.

This paper presents the first part of an extensive investigation addressing the load carrying capacity of stainless steel built-up columns with closely spaced chords that was conducted at the Faculty of Civil Engineering, University of Belgrade [37]. The paper aims to provide reliable experimental and numerical data associated with the material behaviour and cross-section resistance. The experimental programme consisted of tensile and compressive tests on coupons extracted from the flat sheet and final press-braked channel section. The generated results enabled the validation of different Ramberg–Osgood material models from literature. In addition, the results from the corner coupon tests were used to evaluate the quality of existing prediction equations for determining the strength enhancements observed in cold-formed sections and to make comparisons between them. The Finite Element (FE) models of the tensile flat and corner coupon tests were built in order to establish parameters of a ductile damage model and predict the full stress–strain relationship. The ultimate resistance and deformation capacity of press-braked channel sections were determined by stub column tests. Numerical modelling was used to simulate stub column tests after which a parametric study was performed in order to generate data over a wide range of section slenderness and identified dominant impact parameters on the failure mode. The results enabled the assessment of the class 3 slenderness limit and the validation of design rules according to EN 1993-1-4 [5], SE/ASCE 8-02 [38] and the Continuous Strength Method (CSM) [39,40].

The overall aim of this study is to acquire further knowledge about material and cross-section structural behaviour as the first important step towards the development of a suitable design procedure for stainless steel built-up columns [37].

2. Materials

This investigation was concentrated on the most commonly used austenitic stainless steel grade EN 1.4301 (X5CrNi18-10). All test specimens were formed from cold-rolled wide strips with nominal

Table 1
Summary of database for stub column tests.

Reference	Material	Section type	No. of tests
Johnson and Winter [20]	1.4301	Cold-formed hat members	10
Johnson and Winter [21]	1.4301	Two press-braked back-to-back channels	16
Rasmussen and Hancock [22]	1.4301	SHS	2
	1.4301	RHS	2
Bredenkamp and van den Berg [23]	1.4512	Welded I section	2
Talja and Salmi [24]	1.4301	SHS	1
		RHS	2
Burgan et al. [25]	1.4435	CHS	3
	1.4541		
Young and Hartono [26]	1.4301	CHS	4
Kuwamura [27]	1.4301	Press-braked angle	12
	1.4318	Press-braked lipped channel section	12
		Press-braked channel section	11
		Built-up welded I section	16
		SHS	12
		CHS	10
Young and Liu [28]	1.4301	SHS	4
		RHS	8
Gardner and Nethercot [29]	1.4301	SHS	17
		RHS	16
		CHS	4
Young and Lui [30]	Duplex stainless steel	SHS	6
		RHS	3
Gardner et al. [31]	1.4318	SHS	4
		RHS	4
Theofanous et al. [32]	1.4401	OHS	6
Huang and Young [33]	1.4162	SHS	2
		RHS	4
Saliba and Gardner [34]	1.4162	Welded I section	4
Yuan et al. [35]	1.4301	Welded I section	28
	1.4462	Welded RHS	
		Welded SHS	
Fan et al. [36]	S30408	Cold-formed lipped C section	10