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Experimental investigation of local-overall interaction buckling of stainless steel lipped channel columns

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ABSTRACT

The paper describes an experimental programme carried out at the University of Sydney to study the interaction of local and overall buckling in stainless steel lipped channels under axial compression. Three stainless steel alloys were considered: AISI304, AISI430 and 3Cr12. Material tests were carried out to determine the tensile and compressive properties of the flat plate material and of the cold-worked corners. The results reveal nonlinear stress–strain behaviour with low proportionality limit, anisotropy and enhanced strength as a result of cold-working.

A total of 29 column tests were completed with the aim of studying local-overall interaction buckling. The test specimens were designed to fail in the inelastic range to incorporate the effect of the gradual loss of material stiffness into the test results. 11 specimens were tested under a concentrically applied load. The remaining specimens had the load applied with a nominal eccentricity of $L_e/1500$ towards the web. Since the cross-section is singly symmetric, the interaction phenomenon is further affected by the shift in effective centroid resulting from local buckling.

1. Introduction

Stainless steel can be found in a wide variety of structural applications. Because of its excellent corrosion resistance stainless steel is a material of choice in highly aggressive and corrosive environments, such as marine environments, chemical industries and wastewater treatment plants. Its superior corrosion resistance goes hand in hand with reduced maintenance costs and low lifecycle costs, which can offset the relatively high unit price of stainless steel in comparison to carbon steel. In other cases stainless steel is valued because of its ability to retain strength at elevated temperatures [1–3], or because of its aesthetical appeal and architectural value.

A number of reasons can be put forward as to why thin-walled sections offer a particularly interesting field of application for stainless steel. First of all, utilising the post-buckling capacity of locally buckled plate assemblies, thin-walled structural members offer a high strength-to-weight ratio, thus making efficient use of a relatively expensive material. Second, stainless steel is widely available in thin sheets as a result of its popularity in many non-structural applications, such as household appliances. Third, significant strength enhancement of the corner areas can be obtained from the cold-forming process. Furthermore, the use of stainless steel eliminates the natural vulnerability to corrosion which carbon steel thin-walled sections exhibit due to their large ratio of surface to volume.

Stainless steel exhibits a stress–strain behaviour which is distinctively different from that of conventional carbon steel. Generally its stress–strain curve is highly nonlinear with a low proportionality stress, causing the material to lose stiffness at relatively low stress levels [3,4]. Therefore, the governing design rules for carbon steel cannot directly be applied to stainless steel.

Extensive research has been carried out to study singular buckling modes (local, overall and distortional buckling) in stainless steel cold-formed columns [5–10]. However, limited experimental data is available on the interaction of local and overall buckling in stainless steel columns. A number of experimental programmes on stainless steel SHS and RHS [11–16] report ultimate capacities affected by the interaction of local and overall buckling. Experimental data on the local-overall interaction buckling of stainless steel I-columns, consisting of back-to-back channels, has recently been made available [17]. However, data on singly symmetric open section columns are non-existent. Singly symmetric sections distinguish themselves from doubly symmetric sections by the fact that local buckling causes the centroid of the effective section to shift relative to the line of loading, resulting in beam–column action. This papers aims to remedy the lack of experimental data on the interaction of local and overall buckling of singly symmetric stainless steel sections.

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Table 1
Tensile properties of the flat plate material.

Alloy	θ (°)	E_0 (GPa)	$\sigma_{0.01\%}$ (MPa)	$\sigma_{0.2\%}$ (MPa)	σ_u (MPa)	n	r
304	0	192	158	245	689	7	1.00
	30	197	166	243	669	8	1.00
	45	198	184	246	693	10.5	1.00
	90	205	186	250	700	10	1.02
430	0	192	187	280	431	7.5	1.00
	30	209	185	291	443	6.5	1.04
	45	213	205	309	460	7.5	1.10
	90	211	238	301	453	13	1.07
3Cr12	0	195	215	328	475	7	1.00
	30	205	224	339	443	7	1.03
	45	199	214	359	465	6	1.09
	90	220	280	378	489	10	1.15

2. Material properties

Three different stainless steel alloys were considered in this programme: austenitic AISI304, ferritic AISI430 and 3Cr12, which is weldable stainless steel with ferritic-like properties. The corresponding designations in the EN-10088 system [3] are 1.4301, 1.4016 and 1.4003 respectively. The materials were supplied in plate thicknesses of 1.96 mm, 1.98 mm and 1.13 mm respectively.

2.1. Properties of the flat plate material

Tension coupons were cut from the virgin plate material under different angles θ with the rolling direction to study the extent of anisotropy introduced by the rolling process. Testing was carried out in conformance with AS/NZS1391 [18]. Detailed results can be found in [19]. Table 1 summarises the results. E_0 is the initial Young's modulus, $\sigma_{0.01\%}$ is the proportionality limit (defined as the stress corresponding to a 0.01% plastic strain), $\sigma_{0.2\%}$ is the 0.2% proof stress, n is a Ramberg–Osgood parameter and σ_u represents the tensile strength. Static material properties are reported. The parameter n is a measure for the roundness of the stress–strain curve: a lower value of n indicates a more rounded the stress–strain curve and a more pronounced loss of stiffness at lower stress levels. The anisotropy ratio r in Table 1 is defined as the ratio of the 0.2% proof stress in the direction under consideration to the 0.2% proof stress in the rolling direction. It can be concluded from Table 1 that the 430 and 3Cr12 alloys exhibit modest anisotropy while the 304 material displays very little, if any, anisotropic behaviour in tension. Generally, the rolling direction ($\theta = 0$) will exhibit the lowest 0.2% proof stress, while the transverse direction ($\theta = 90°$) will generally display the highest 0.2% proof stress. The maximum anisotropy ratio is encountered for the 3Cr12 material in the transverse direction, where an increase of 15% in the 0.2% proof stress is observed relative to the rolling direction. Table 1 also illustrates the highly nonlinear behaviour of stainless steel alloys, which is reflected in low proportionality stresses and low n-values.

Compressive coupon tests were carried out on the virgin flat plate material under different angles θ with the rolling direction. A special jig was devised for compression coupon testing, which is shown in Fig. 1. Rectangular coupons with nominal dimensions of 25 mm by 93 mm were cut from the flat plate material. Seven coupons were glued together to build up a nominal thickness of 8.4 mm and were machined square. The specimens were instrumented with two strain gauges at mid-length to allow an accurate determination of the initial elastic modulus. The gauges typically reached the end of their measuring range around 1.5% strain, which allowed a sufficient portion of the stress–strain curve to be determined. When placed in the jig, the coupons protruded approximately 3 mm beyond the top of the jig, which was again amply sufficient to reach 1.5% strain. The specimens were greased before being placed in the jig, to eliminate friction between the specimen surfaces and the jig. The six bolts were loosely tightened to prevent buckling of the specimen about its weak axis, while at the same time allowing lateral expansion of the specimen due to the Poisson's effect. Complete details of the test procedure are described in [19]. The test results are summarised in Table 2 and shown in Fig. 1 for the longitudinal direction. It can be seen that, again, the anisotropy is the most pronounced in the ferritic 430 alloy and the ferritic-like 3Cr12 alloy, and the least manifest in the austenitic 304 alloy.

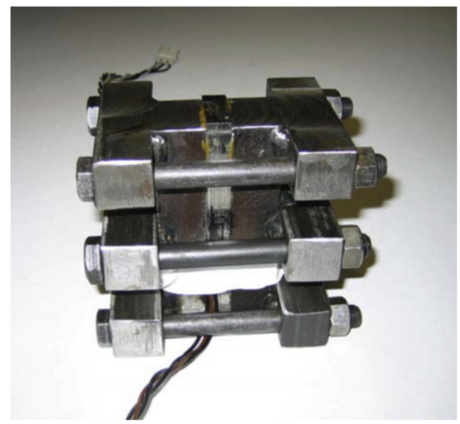

Fig. 1. Compressive test jig.

Comparison between Tables 1 and 2 illustrates that stainless steel alloys can exhibit different properties depending on the direction of the applied stress: tension or compression. The 0.2% proof stress for compression is lower than for tension for alloys 304 and 430 but nearly the same for the 3Cr12 material.

2.2. Properties of the corner material

All specimens were manufactured using a conventional brake-pressing procedure. In order to study the effect of the cold-working on the material properties, small tensile and compressive coupons were cut from the corner zones of a channel. Details of the test programme can be found in [19]. Table 3 lists the results (LT = longitudinal tension, LC = longitudinal compression). When comparing the material properties of the corners with the properties of the flat material in tension (Table 1) and compression (Table 2), it is clear that the cold-forming process has a profound effect on the material properties and greatly increases the strength of the material. This can also be seen in Fig. 1 which depicts the compressive stress–strain curves of the corners versus the compressive stress–strain curves of the flat plate materials. Compressive testing of the 430 corners proved to be impractical due to the small radius and limited thickness of the specimens and consequently results are not available for this case. The initial