Compression strength of stainless steel cross-sections

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ABSTRACT

A conceptually new approach which recognises the continuous nature of the stress-strain characteristic of stainless steel has recently been developed by the authors for the prediction of the strength of compressed plate elements in stainless steel members. This method does not use the classification system found in modern codes dealing with the structural design of carbon steel members. The original development was limited to plate elements supported on both longitudinal edges; the basic concept is expanded herein to cover a wider range of cases. The resulting design procedure forms part of a general treatment of stainless steel structural members that predicts resistances significantly in excess of those obtained from currently available design methods. These resistances are found to accord well with the observed strength of sections obtained in laboratory tests.

KEYWORDS

Cross-section slenderness, Cross-section strength, Deformation capacity, Enhanced corner strength, Open sections, Stainless steel.

1. INTRODUCTION

The physical characteristics of stainless steel - including high strength, stiffness and ductility, weldability, durability, ease of forming and machining, good fire resistance and readily re-

usable and recyclable - makes the material ideally suited to use in construction. Recent years have seen significant advances towards effectively utilising these properties, such as the introduction or major revision of the principal structural stainless steel design standards worldwide, an enhanced range of products and wider product availability; all of this has been supported by heightened research activity. However, stainless steel is still viewed as an extravagant solution to structural engineering problems, and although the emergence of design codes is an important step forward, their inefficiency (due largely to overly-simplistic material modelling) is inhibiting more widespread use.

One of the principal drawbacks to these codes is that they were based on the rather limited amount of structural performance data available and a significant factor in their preparation was the initial need to ensure that a designer familiar with the carbon steel rules would be able to make a straightforward transition to stainless steel structural design. As a result, the authors were obliged to use a simplified elastic, perfectly-plastic material model. This model is acceptable for carbon steel that exhibits a sharply defined yield point, followed by a plastic yield plateau. For stainless steel, though, where there is no sharply defined yield point and substantial strain hardening is possible, this model leads to overly conservative designs.

It is clear that for a material with high initial cost, efficient design is paramount, and a more rigorous design approach that more accurately recognises and exploits the particular features of stainless steel can be justified. Gardner [1] initially focused on the austenitic family of stainless steels since these are the most widely used grades for structural applications throughout the world, though more recent work has since demonstrated extension of the method to other non-linear materials [2]. Test results for other grades of stainless steel have been incorporated in the present study to validate the method as a general design tool.

2. BACKGROUND

2.1 Laboratory testing

A laboratory testing programme was carried out to investigate the behaviour of austenitic stainless steel cross-sections and members. Tests were conducted on square, rectangular and circular hollow sections (SHS, RHS and CHS respectively). Tensile and compressive coupon tests were carried out on flat material cut from the faces of finished SHS and RHS to determine the material stress-strain behaviour. Coupons cut from the corner regions of the cross-sections were also tested to investigate the effect of strain hardening. Stub column tests were conducted on SHS, RHS and CHS to enable the development of a relationship between cross-section slenderness β and deformation capacity ϵ_{LB} , and to determine ultimate load carrying capacities [3]. Member tests on SHS and RHS beams and columns were conducted to investigate structural behaviour and to determine ultimate load carrying capacities [4]. Initial geometric imperfections and residual stresses were measured to aid the explanation of structural performance and to use as basic data in numerical models.

The laboratory test results have led to an improved understanding of the structural behaviour of stainless steel and have been used as a means of validating numerical models. The results have also formed part of the validation of a proposed new design procedure.

2.2 Numerical modelling

Sophisticated numerical models have been developed using the finite element (FE) package ABAQUS. The models have included features such as measured (non-linear) material properties, measured geometry, rounded and enhanced strength corners, initial local and global geometric imperfections and residual stresses. Formulations have been also developed

to provide general expressions for initial geometric imperfections, residual stresses and enhanced corner material properties, allowing a consistent approach to the generation of further results through parametric studies [5].

2.3 Proposed design method for hollow sections

2.3.1 Concept

The cross-section strength of stainless steel members is currently assessed on a similar basis to the cross-section strength of carbon steel members [6]. The cross-section is initially placed into one of a number of possible behavioural classes (with the number depending on the particular design code), and subsequently its strength is limited by either material yielding of the gross section, with either a plastic or elastic distribution of stresses, or yielding of an effective section (to account for local buckling) with an elastic stress distribution.

A new design approach has been proposed by Gardner [1], Gardner and Nethercot [7] and Gardner et al [8] that replaces these discrete behavioural classes with a continuous measure of the deformation capacity of the cross-section. The strength of the cross-section may then be determined using this deformation capacity in conjunction with a material model that accurately reflects the rounded nature of the stainless steel stress-strain curve.

2.3.2 Development

The deformation capacity ε_{LB} of a cross-section was defined as the deformation δ_u corresponding to the peak of the load-end shortening curve, obtained from stub column tests (in pure compression) divided by the stub column length. All available stub column test results were used to develop a relationship between element slenderness β , defined by Eq. 1

(based on the most slender element in the cross-section) and normalised element deformation capacity $\varepsilon_{LB}/\varepsilon_0$, where ε_0 is the elastic strain at the material 0.2% proof stress. The results from tests on SHS were assumed to relate approximately to plate elements with simply-supported boundary conditions, since the four elements of the cross-section provide equal restraint to one another [9]. In the case of rectangular hollow sections, however, greater edge restraint is applied to the more slender sides of the cross-section by the less slender sides. As a result, higher buckling curves can be applied to the more slender sides of rectangular hollow sections, and clearly an increase in aspect ratio produces an increase in edge restraint. A modification factor involving the aspect ratio was incorporated into the basic relationship obtained for the SHS to arrive at a general expression for the hollow sections [1].

The local buckling strain of a cross-section was, thus, obtained from the proposed equations, and the compound Ramberg-Osgood model [1], developed on the basis of a similar expression proposed by Mirambell and Real [10], was used to obtain the corresponding local buckling stress σ_{LB} . Compression resistance is thus defined as the product of the local buckling strength σ_{LB} and the gross area of the cross-section A_g .

2.3.3 Validation

Results from the proposed method have been compared against all available test results on austenitic stainless steel hollow sections [1, 8]. The comparison showed that the proposed method gives excellent prediction of the test results, and offers a considerable benefit over the Eurocode approach. For SHS and RHS compression resistance, the Eurocode design method predicts, on average, 78% of the test failure load with a standard deviation of 13%, whereas the proposed design method predicts 95% of the test failure load with a standard deviation of 8% resulting in a 25% increase in cross-sectional resistance.

3. EXTENSION OF PROPOSED METHOD

3.1 Test results used for open sections

The success of the proposed method for hollow sections opens the way for its extension to cover all types of sections. All available test results on stainless steel open sections as reported by Kuwamura [11], Stangenberg [12], Lecce and Rasmussen [13] have been analysed with a view to obtaining a generalised method for all stainless steel sections comprising flat plate elements. A similar treatment for circular sections is described elsewhere [1, 7].

Kuwamura [11] investigated the local buckling behaviour of thin-walled stainless steel sections through an extensive testing scheme. A total of 63 stub columns from Grades 1.4301 and 1.4318 with angle, channel, lipped channel, H and square hollow cross-sections were tested. All the sections were cold-formed by press-braking at the corners apart from the welded H sections. Stangenberg [12] reported stub column tests on welded H sections, conducted as a part of the ECSC funded project ‘Development of use of stainless steel in construction’. Three specimens were made from Grade 1.4301 while the other one was from Grade 1.4462. Lecce and Rasmussen [13] tested lipped channel stub columns produced from Grades 1.4301, 1.4016 and 1.4003 to study the distortional buckling behaviour of cold-formed stainless steel sections. Table 1 gives a summary of the stub columns with outstands used in the present study.

The slenderness parameter β is defined by Eq. 1, and has been determined on the basis of the most slender element in the cross-section.

$$\beta = \frac{b}{t} \sqrt{\frac{\sigma_{0.2}}{E_0}} \sqrt{\frac{4}{k}} \quad (1)$$

where

$\sigma_{0.2}$ is the material 0.2% proof stress in compression

E_0 is the material Young's modulus

b is the flat face width measured between centrelines (except for the welded I sections) of adjacent faces as shown in Fig. 1

t is the wall thickness of the cross-section

k is the buckling coefficient whose value for internal and outstand elements in the case of pure compression is taken as 4.0 and 0.43 respectively [14].

3.2 Design curve for local buckling strain ϵ_{LB}

Following the same concept as for the hollow sections [8], a generalised relationship was established for all the cross-sections containing flat plate elements. The relationship between the cross-section slenderness β and normalised local buckling strain ϵ_{LB}/ϵ_0 is shown in Fig. 2.

From Fig. 2 it is observed that all cross sections follow a common trend when the slenderness β of the most slender element of a cross-section is calculated using the appropriate buckling coefficient k . For outstand elements in pure compression the buckling coefficient is taken as 0.43, whereas for all internal compression elements its value is taken as 4.0. Initial studies [1] have also indicated that the theoretical buckling coefficients k_s given in Tables 5.3.2 and 5.3.3 of ENV 1993-1-1 [14] may be adopted in Eq. 1 to account for other linearly varying stress distributions (eg. pure bending). All the test results were simulated using sophisticated FE models that include effects of corner enhancement, predicted initial imperfections following established guidelines and thermal residual stresses in the case of welded H

sections. The predictions of the developed numerical models were in good agreement with the test results [15]; some additional results were generated using the validated FE technique for cases where test results were scarce as seen in Fig. 2. The generated points also follow the same path as shown in Fig. 3. A regression analysis was performed to obtain the generalised relationship between the cross-section deformation capacity and cross-section slenderness which is given by Eq. 2. Fig. 3 compares Eq. 2 to all the stub column results.

$$\text{For all sections, } \frac{\varepsilon_{LB}}{\varepsilon_0} = \frac{7.547}{\beta^{2.527 - 0.221 \beta}} \quad (2)$$

3.3 Local buckling stress σ_{LB} using the material stress-strain behaviour

The local buckling strain ε_{LB} of a cross-section can be determined from Eq. 2 and this strain can be used to obtain the local buckling stress σ_{LB} from the material stress-strain relationship. For practical cases it is preferable to establish a stress-strain relationship such that the stress can be directly obtained from the strain. The compound Ramberg-Osgood model, as expressed in Eqs 3 and 4, can be used to model the stainless steel behaviour very accurately, but relates strain as a function of stress. Since stress cannot be obtained directly from this model, the material behaviour can be presented in a tabular form to enable designers to obtain σ_{LB} directly from ε_{LB} without the need for iteration.

$$\varepsilon = \frac{\sigma}{E_0} + 0.002 \left(\frac{\sigma}{\sigma_{0.2}} \right)^n \quad (\sigma \leq \sigma_{0.2}) \quad (3)$$

$$\varepsilon = \frac{(\sigma - \sigma_{0.2})}{E_{0.2}} + \left(0.008 - \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}} \right) \left(\frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}} \right)^{n'_{0.2,1.0}} + \varepsilon_{t0.2} \quad (\sigma \geq \sigma_{0.2}) \quad (4)$$

where

$\sigma_{0.2}$ and $\sigma_{1.0}$ are 0.2% and 1% proof stress respectively

$\varepsilon_{t0.2}$ is the total strain at the 0.2% proof stress

n and $n'_{0.2,1.0}$ are strain hardening coefficients

E_0 is the initial Young's Modulus

$E_{0.2}$ is the stiffness at 0.2% proof stress.

From a structural point of view, it is an essential requirement to know the basic stress-strain behaviour of a material prior to using it in practice. Standard coupons are tested to produce this basic stress-strain behaviour. In the case of stainless steel, numerous coupon tests have been reported by Rasmussen and Hancock [16], Talja and Salmi [17], Macdonald et al [18], Mirambell and Real [10], Stangenberg [12]; Gardner [1], Young and Liu [19]. Most of these involved austenitic Grade 1.4301 since this is the most widely used type of stainless steel. Coupons were cut from both cold-formed and press-braked sections. The test results are summarised in Table 2 stating the average values for Young's modulus E_0 , $\sigma_{1.0}/\sigma_{0.2}$ and the compound Ramberg-Osgood parameters n and $n'_{0.2,1.0}$.

These tabulated values are used to develop Tables 3, 4 and 5 following Eqs. 3 and 4, which will be used to obtain the local buckling stress σ_{LB} by knowing ϵ_{LB} from Eq. 2 and $\sigma_{0.2}$.

3.4 Validation of the proposed technique

The proposed technique for the determination of compressive strength involves the following parameters:

- i. Cross-section slenderness β for the most slender element using Eq.1
- ii. Local buckling strain ϵ_{LB} using Eq. 2
- iii. Local buckling stress σ_{LB} from the appropriate table (Table 3, 4 or 5)
- iv. Compressive strength $N_{c,Rd}$ (or F_u) is equal to σ_{LB} times the gross area A_g

The compressive strengths of all the stub columns have been determined following these steps and the results are compared to the test results in Fig. 4.

From Fig. 4 it is observed that the predictions are somewhat scattered, the standard deviation being 0.21 with a mean of 1.07. For the relatively stocky sections with $\beta \leq 1.5$, most of the predictions are less than the test results, whereas for slender specimens the predicted strengths are rather high when compared to the test results. This comparison clearly suggests that some modifications are required to make predictions closer to the test results.

4. ANALYSIS OF RESULTS AND PROPOSED MODIFICATIONS

The proposed approach directly uses the material stress-strain behaviour to obtain the local buckling stress for the stub columns. In reality, stub column stress-strain curves differ from material coupon stress-strain curves due to the presence of residual stresses and enhanced strength at the corners. Thermal residual stresses, in the case of hollow and H sections, have been shown to have little influence on stub column behaviour [1 & 15] and the bending residual stresses are re-introduced into the coupons in the process of testing. Enhanced corner strength, on the other hand, plays a very significant role in the case of relatively stocky sections and the use of only the basic material stress-strain curve underestimates the compressive strength. As the section becomes more slender, the corner region loses its significance, gradually, and the local plate buckling at stresses below $\sigma_{0.2}$ dominates failure. Post buckling behaviour has also been found to be significant in the case of slender columns, causing the stub column stress-strain behaviour to deviate from that of the coupon before reaching the peak stress [1]. This causes some overestimation in compressive strength for the relatively slender cross-sections with $\beta > 1.5$. These features are illustrated in Fig. 5.

4.1 Correction for sections with enhanced corner strength

Stainless steel exhibits pronounced strain hardening, resulting in the corner regions of cold-formed sections having 0.2% proof strengths much higher than that of the flat material. Failure to allow for these enhanced strength regions in design leads to under-predictions of load carrying capacity. This effect has been found to be very important in the case of stocky sections since they normally contain a larger proportion of corner area. A correction factor is, therefore, required to explicitly include the effects of corner enhancements and to bring the predictions closer to the test results.

Ashraf et al [20] proposed models to predict the 0.2% proof strength and ultimate strength of corner regions after a comprehensive investigation of the available test results. Separate models were proposed to allow for the difference between the roll-forming and press-braking processes. Two different correction factors are proposed herein for the prediction of cross-section strength of the roll-formed and press-braked specimens.

4.1.1 Correction for roll-formed sections

The material properties of the flat region of roll-formed sections are different from those of the virgin material because of the cold-work done in the roll-forming process. The following expressions hold true for a roll-formed section,

$$\begin{aligned} F_u &= A_f \cdot \sigma_{0.2,f} + A_c \cdot \sigma_{0.2,c} \\ &= A_g [A_f/A_g \cdot \sigma_{0.2,f} + A_c/A_g \cdot \sigma_{0.2,c}] \\ &= A_g [(1 - k_{cor}) \cdot \sigma_{0.2,f} + k_{cor} (0.82\sigma_{u,f})] \\ &= A_g [(1 - k_{cor}) \cdot \sigma_{0.2,f} + k_{cor} (0.82 \times 1.61 \sigma_{0.2,f})] \\ &= A_g \cdot \sigma_{0.2,f} (1 + 0.32k_{cor}) \end{aligned} \tag{5}$$

where,

F_u = peak load of the stub column

A_f = area of the flat region

A_c = area of the corner region

A_g = gross area, $A_f + A_c$

k_{cor} = proportion of corner region, A_c/A_g

$\sigma_{0.2,f}$ = 0.2% proof stress of the flat material

$\sigma_{0.2,c}$ = 0.2% proof stress of the corner material ($= 0.82 \sigma_{u,f}$) [20]

$\sigma_{0u,f}$ = ultimate strength of the flat material ($= 1.61 \sigma_{0.2,f}$) [1]

Thus the cross-section strength of a roll-formed section should be multiplied by the factor $(1 + 0.32k_{cor})$ to account for the material strength enhancements in the corner (and flat) regions.

4.1.2 Correction for press-braked sections

In the case of press-braked sections, the material properties of the flat region can be taken to be the same as the virgin material, increases in the 0.2% proof strength only at the corners.

The strength of a press-braked section can be expressed as follows,

$$\begin{aligned}
 F_u &= A_f \cdot \sigma_{0.2,v} + A_c \cdot \sigma_{0.2,c} \\
 &= A_g [A_f/A_g \cdot \sigma_{0.2,v} + A_c/A_g \cdot \sigma_{0.2,c}] \\
 &= A_g [(1 - k_{cor}) \cdot \sigma_{0.2,v} + k_{cor} 1.881 / \left(\frac{r_1}{t}\right)^{0.194} \cdot \sigma_{0.2,v}] \\
 &= A_g \cdot \sigma_{0.2,v} [1 + \{1.881 / \left(\frac{r_1}{t}\right)^{0.194} - 1\} k_{cor}]
 \end{aligned} \tag{6}$$

where,

$\sigma_{0.2,v}$ = 0.2% proof stress of the flat (virgin) material

$$\sigma_{0.2,c} = 0.2\% \text{ proof stress of the corner material } [=1.881/\left(\frac{r_1}{t}\right)^{0.194} \cdot \sigma_{0.2,v}] [20]$$

Thus the cross-section strength of a press-braked section should be multiplied by the factor

$[1 + \{1.881/\left(\frac{r_1}{t}\right)^{0.194} - 1\}k_{cor}]$, to account for the localised corner strength enhancements.

4.2 Correction for slender sections with $\beta > 1.5$

A simple linear regression analysis was performed to obtain a reduction factor for the slender sections. The local buckling stress obtained from the material stress-strain table should be multiplied by the factor $(-0.154\beta + 1.186)$ to obtain the appropriate value.

It should be noted that for a slender cross-section with corner regions, the local buckling stress obtained from the table should be multiplied by two factors – enhancement for corner regions followed by a reduction for its slenderness.

5. DETAILED COMPARISONS

Strengths of all the stub columns have been predicted using the proposed method with appropriate corrections and the detailed results are given in Table 6. A summary of the predictions is given in Table 7.

From Table 7 it is observed that the proposed corrections make the predictions closer to the test results – average prediction and standard deviation for all sections become 1.00 and 0.12, in place of 1.07 and 0.21, respectively. Figure 11 shows a comparison of the predictions to the test results after using the corrections. The reduction in scatter is clear if Fig.6 is compared with Fig. 4.

However some predictions for SHS stub columns formed by welding two press-braked channel sections tip-to-tip (Kuwamura, Grade 1.4318 [11]) are surprisingly high and inconsistent with the other predictions. The FE models for these stub columns provide some answers to this contradiction. The ultimate loads reported for these columns are significantly smaller than the FE results. Table 8 lists the FE results and compares the predicted strength to the test and FE results. Both the average and scatter shows a significant improvement if the proposed predictions are compared to the FE results rather than the reported test results. It is worth mentioning that apart from these stub columns all the numerical predictions are in good agreement with the test results [15].

6. CONCLUSIONS

This paper has explained how test and numerical results for stainless steel sections have been used to develop and calibrate a new design method for stainless steel structures which uses a common technique to determine the compressive strength for all types of cross-sections without the need for traditional section classification. This new method offers material savings of around 25% for hollow sections over current design methods, whilst retaining safe-side predictions, and for a similar volume of calculation. Further work is underway to extend this method for all types of loading and expedite its introduction into common use as a practical design tool.

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Table 1 Test results used in the present study.

Reference	Grades	Cross-section	No. of stub columns	β
[11]	1.4301, 1.4318	Angle	12	0.89 – 3.17
		Channel	11	0.91 – 2.67
		Lipped channel	12	1.24 – 3.58
		H-section	16	0.93 – 3.99
		SHS	12	0.61 – 3.58
[12]	1.4301, 1.4462	H- section	4	0.90 – 1.94
[13]	1.4301, 1.4016, 1.4003	Lipped channel	10	1.81 – 2.21

Table 2 Summary of the coupon test results.

Type	Grade	E_0 (N/mm ²)	n	$n'_{0.2,1.0}$	$\sigma_{1.0}/\sigma_{0.2}$
Press-braked	1.4301	194000	8.5	1.66	1.13
	1.4318	187000	9.6	2.7	1.08
Roll-formed	1.4301	201000	4.3	2.7	1.26

Table 3 Local buckling stress σ_{LB} (N/mm²) for press-braked sections of Grade 1.4301

ϵ_{LB}	$\sigma_{0.2}$ (N/mm ²)								
	240	260	280	300	340	380	420	460	500
0.001	172	178	184	187	191	192	194	194	194
0.002	218	233	248	263	289	313	333	350	363
0.003	237	255	273	290	324	356	388	416	443
0.004	246	265	285	305	343	381	416	451	485
0.005	251	271	291	312	352	391	431	469	507
0.006	255	276	296	317	358	399	439	479	519
0.007	258	280	301	322	364	405	446	487	528
0.008	262	283	305	326	368	411	453	494	536
0.009	265	287	308	330	373	416	458	501	543
0.010	268	290	312	334	377	421	464	507	550
0.012	273	296	318	341	385	430	474	518	562
0.014	278	301	324	347	392	438	483	528	573
0.016	283	306	329	353	399	445	491	537	583
0.018	287	311	335	358	405	452	499	546	593
0.020	292	315	339	363	411	459	507	554	602
0.024	299	324	349	373	423	472	521	570	619
0.028	307	332	357	382	433	483	534	584	634
0.032	313	339	365	391	443	494	546	597	649
0.036	320	346	373	399	452	505	558	610	663
0.040	326	353	380	407	461	515	569	622	676
0.050	340	369	397	425	482	538	594	651	707
0.060	354	383	412	442	501	560	618	677	736
0.070	366	397	427	457	518	579	640	701	762
0.080	378	409	441	472	535	598	661	724	787
0.090	389	422	454	486	551	616	681	746	811
0.100	400	433	466	500	566	633	700	767	833

Table 4 Local buckling stress σ_{LB} (N/mm²) for press-braked sections of Grade 1.4318

ϵ_{LB}	$\sigma_{0.2}$ (N/mm ²)								
	350	400	440	480	520	560	600	650	700
0.001	187	187	187	187	187	187	187	187	187
0.002	297	324	341	354	363	367	370	372	373
0.003	333	372	402	430	456	478	498	518	533
0.004	352	397	432	466	499	530	559	593	624
0.005	361	410	450	488	525	561	594	635	674
0.006	365	416	457	497	537	576	615	662	707
0.007	368	420	461	502	543	583	624	673	723
0.008	371	423	465	506	548	589	630	681	731
0.009	373	426	468	510	551	593	634	686	737
0.010	375	428	470	513	554	596	638	691	742
0.012	378	432	474	517	560	602	645	698	750
0.014	381	435	478	521	564	607	650	704	757
0.016	383	438	481	525	568	611	655	709	762
0.018	385	440	484	528	571	615	659	713	767
0.020	387	442	487	531	575	618	662	717	772
0.024	391	447	491	536	580	624	669	724	779
0.028	394	450	495	540	585	629	674	730	786
0.032	397	453	499	544	589	634	679	736	792
0.036	399	456	502	547	593	638	683	740	797
0.040	402	459	505	551	596	640	688	745	802
0.050	407	465	511	558	604	650	697	755	813
0.060	411	470	517	564	611	658	705	764	822
0.070	415	475	522	569	617	664	712	771	830
0.080	419	479	527	574	622	670	718	778	838
0.090	422	483	531	579	627	676	724	784	845
0.100	426	486	535	583	632	681	730	790	851

Table 5 Local buckling stress σ_{LB} (N/mm²) for roll-formed sections of Grade 1.4301

ϵ_{LB}	$\sigma_{0.2}$ (N/mm ²)								
	200	240	280	320	360	400	440	480	520
0.001	131	148	161	171	179	184	188	192	196
0.002	174	203	229	252	274	292	309	324	340
0.003	200	235	268	299	328	356	381	405	431
0.004	216	256	295	332	367	400	431	461	493
0.005	225	268	310	351	391	430	468	504	543
0.006	232	276	320	364	407	448	489	530	574
0.007	237	283	328	373	418	461	505	547	592
0.008	241	288	335	381	426	472	516	560	608
0.009	245	293	340	387	434	480	526	572	622
0.010	248	297	345	393	441	488	535	581	631
0.012	254	304	354	403	452	501	549	598	651
0.014	259	310	361	412	461	511	561	611	665
0.016	263	316	367	419	470	521	572	622	676
0.018	268	320	373	426	478	529	581	632	687
0.020	271	325	378	431	484	537	590	642	699
0.024	277	333	388	442	497	551	605	658	716
0.028	284	340	396	451	508	563	618	673	733
0.032	289	346	403	461	517	574	630	687	749
0.036	294	352	410	468	526	584	641	698	760
0.040	298	357	416	476	534	592	652	710	773
0.050	308	369	430	491	552	613	673	735	803
0.060	316	379	442	505	568	630	693	755	823
0.080	331	397	463	529	594	660	725	791	863
0.100	344	412	480	548	616	685	752	821	896

Table 6 Comparison of predicted results with tests.

Ref.	Type, Grade	Nom. size	β	ϵ_{LB}	σ_{LB} N/mm ²	Cor. factor	A mm ²	Pred F_u kN	Test F_u kN	Pred F_u /Test F_u
Kuwamura [11]	L 1.4301	25 × 25 × 3	0.89	0.0131	301.1	1.13	130	44.1	55.9	0.79
		30 × 30 × 3	1.08	0.0084	286.8	1.11	158	50.5	59.4	0.85
		40 × 40 × 3	1.45	0.0043	268.8	1.08	217	63.3	66.9	0.95
		40 × 40 × 3	1.45	0.0044	269.4	1.09	217	63.6	65.6	0.97
		50 × 50 × 3	1.83	0.0027	250.1	0.96	276	66.5	68.7	0.97
		60 × 60 × 3	2.17	0.0020	234.5	0.90	335	70.4	69.6	1.01
	L 1.4318	25 × 25 × 3	1.32	0.0118	582.5	1.13	135	89.3	79.7	1.12
		30 × 30 × 3	1.58	0.0081	570.5	1.06	162	97.7	89.8	1.09
		40 × 40 × 3	2.09	0.0048	539.0	0.93	225	113.2	108.7	1.04
		40 × 40 × 3	2.10	0.0048	539.0	0.94	225	114.3	100.2	1.14
		50 × 50 × 3	2.65	0.0033	483.0	0.83	286	114.6	108.7	1.05
		60 × 60 × 3	3.17	0.0027	437.9	0.74	347	112.2	106.4	1.06
Kuwamura [11]	C 1.4301	50 × 25 × 3	0.91	0.0132	303.5	1.14	258	89.3	106.0	0.84
		80 × 40 × 3	1.48	0.0044	271.4	1.08	431	126.8	134.2	0.94
		100 × 50 × 3	1.88	0.0028	254.1	0.95	555	134.1	146.2	0.92
		100 × 50 × 3	1.87	0.0028	254.1	0.95	555	134.3	140.4	0.96
		150 × 50 × 3	1.88	0.0028	254.1	0.94	699	166.7	156.0	1.07
		50 × 50 × 3	1.87	0.0028	254.1	0.98	404	100.7	125.0	0.81
	C 1.4318	50 × 25 × 3	1.30	0.0126	582.5	1.14	267	178.2	186.2	0.96
		80 × 40 × 3	1.88	0.0060	556.0	0.97	451	242.2	229.7	1.05
		100 × 50 × 3	2.41	0.0039	509.4	0.87	571	252.3	233.8	1.08
		100 × 50 × 3	2.44	0.0038	504.8	0.86	570	247.3	229.6	1.08
Kuwamura [11]	Lip. C 1.4301	100 × 50 × 20 × 3	1.24	0.0065	278.0	1.20	641	213.1	211.4	1.01
		150 × 50 × 20 × 3	1.88	0.0028	250.6	0.97	791	193.2	197.0	0.98
		150 × 65 × 20 × 3	1.89	0.0028	250.6	0.96	873	211.1	214.8	0.98
		200 × 75 × 25 × 3	2.54	0.0017	216.5	0.84	1104	201.8	232.8	0.87
		35 × 17 × 7 × 1	1.29	0.0062	288.9	1.10	70	22.3	23.7	0.94
		50 × 17 × 7 × 1	1.97	0.0026	256.3	0.95	88	21.5	21.7	0.99
		50 × 25 × 7 × 1	1.97	0.0026	256.3	0.95	96	23.3	24.3	0.96
		70 × 25 × 8 × 1	2.71	0.0016	217.8	0.82	120	21.4	26.1	0.82
	Lip. C 1.4318	100 × 50 × 20 × 3	1.75	0.0068	557.6	1.01	659	372.8	350.2	1.06
		150 × 50 × 20 × 3	2.67	0.0034	483.8	0.85	807	331.6	317.9	1.04
		150 × 65 × 20 × 3	2.67	0.0034	483.8	0.84	898	362.9	342.3	1.06
		200 × 75 × 25 × 3	3.58	0.0025	415.1	0.68	1139	319.5	377.8	0.85
Lecce & Rasmussen [13]	Lip. C 1.4301	105 × 90 × 13 × 2	1.92	0.0025	229.2	0.95	565	123.3	116.0	1.06
		105 × 90 × 13 × 2	1.91	0.0025	229.2	0.95	565	123.5	116.0	1.06
		105 × 90 × 13 × 2	1.90	0.0025	229.2	0.96	565	123.7	116.0	1.07
		105 × 90 × 13 × 2	1.90	0.0025	229.2	0.96	565	123.7	116.0	1.07
	Lip. C 1.4016	67 × 57 × 8 × 1.13	2.21	0.0021	243.6	0.90	211	46.2	50.0	0.92
		67 × 57 × 8 × 1.13	2.21	0.0021	243.6	0.90	211	46.2	50.0	0.92
		55 × 55 × 8 × 1.13	1.82	0.0030	264.9	0.97	188	48.3	51.0	0.95
		55 × 55 × 8 × 1.13	1.81	0.0030	264.9	0.97	188	48.4	51.0	0.95
	Lip. C 1.4003	105 × 85 × 15 × 2	2.10	0.0027	312.7	0.92	555	160.4	162.0	0.99
		105 × 85 × 15 × 2	2.10	0.0027	312.7	0.92	555	160.4	162.0	0.99

Table 6 (contd.) Comparison of predicted results with tests.

Ref.	Type, Grade	Nom. size	β	ϵ_{LB}	σ_{LB} N/mm ²	Cor. factor	A mm ²	Pred F_u kN	Test F_u kN	Pred F_u /Test F_u
Kuwaremura [11]	H 1.4301	50 × 50	0.93	0.0116	292.5	1.00	427	124.9	152.8	0.82
		50 × 100	1.85	0.0026	244.5	0.90	709	156.3	192.8	0.81
		100 × 50	1.17	0.0068	277.0	1.00	571	158.2	171.1	0.92
		100 × 75	1.40	0.0046	266.6	1.00	722	192.5	199.9	0.96
		100 × 100	1.86	0.0026	244.5	0.90	863	189.6	203.4	0.93
		150 × 100	1.86	0.0026	244.5	0.90	1012	222.4	207.7	1.07
		200 × 100	2.39	0.0017	215.3	0.82	1157	203.7	206.1	0.99
		200 × 150	2.80	0.0014	199.0	0.75	1460	219.3	231.4	0.95
	H 1.4318	50 × 50	1.30	0.0116	579.8	1.00	435	252.4	253.4	1.00
		50 × 100	2.67	0.0031	472.6	0.77	730	267.2	289.7	0.92
		100 × 50	1.67	0.0070	563.0	0.93	591	309.2	279.5	1.11
		100 × 75	1.99	0.0050	543.0	0.88	739	352.7	309.9	1.14
		100 × 100	2.65	0.0032	477.2	0.78	888	329.7	323.4	1.02
		150 × 100	2.64	0.0032	477.2	0.78	1041	387.2	310.1	1.25
		200 × 100	3.42	0.0024	406.2	0.66	1094	292.9	311.5	0.94
		200 × 150	3.99	0.0022	385.6	0.57	1491	328.7	359.7	0.91
Stan. [12]	H 1.4301 1.4462	160 x 80	0.90	0.0146	348.8	1.00	2430	847.7	885.0	0.96
		160 x 160	0.92	0.0137	346.1	1.00	4074	1410.1	1440.0	0.98
		320 x 160	1.94	0.0028	382.0	0.89	4570	1549.1	1430.0	1.08
		160 x 160	1.19	0.0132	569.0	1.00	4094	2329.7	2590.0	0.90
[17]	SHS 1.4301	60 x 60 x 5	0.57	0.0720	749.2	1.03	999	770.9	801.0	0.96
[16]	SHS 1.4306	80 x 80 x 3	1.187	0.0108	511.0	1.02	908	473.2	485.0	0.98
		80 x 80 x 3	1.176	0.0110	512.3	1.02	900	470.3	471.0	1.00
Kuwaremura [11]	SHS 1.4301	50 x 50 x 3	0.61	0.0348	353.3	1.18	515	215.5	241.0	0.89
		75 x 75 x 3	0.92	0.0128	305.8	1.10	814	274.9	282.4	0.97
		100 x 100 x 3	1.24	0.0065	285.2	1.08	1104	339.5	323.2	1.05
		125 x 125 x 3	1.58	0.0039	270.9	1.00	1400	379.2	353.8	1.07
		150 x 150 x 3	1.90	0.0027	254.4	0.94	1686	403.1	363.9	1.11
		200 x 200 x 3	2.53	0.0017	220.8	0.83	2265	413.3	364.8	1.13
	SHS 1.4318	50 x 50 x 3	0.86	0.0320	622.5	1.15	542	388.3	377.5	1.03
		75 x 75 x 3	1.30	0.0125	592.8	1.09	855	553.2	459.4	1.20
		100 x 100 x 3	1.77	0.0067	570.9	0.98	1132	632.6	468.7	1.35
		125 x 125 x 3	2.23	0.0044	534.0	0.89	1451	687.1	480.5	1.43
		150 x 150 x 3	2.68	0.0033	487.7	0.81	1760	694.0	483.0	1.44
		200 x 200 x 3	3.58	0.0025	419.5	0.66	2346	646.4	511.9	1.26

Table 6 (contd.) Comparison of predicted results with tests.

Ref.	Type, Grade	Nom. size	β	ϵ_{LB}	σ_{LB} N/mm ²	Cor. factor	A mm ²	Pred F_u kN	Test F_u kN	Pred F_u /Test F_u
Gardner [1]	SHS 1.4301	80 x 80 x 4	1.02	0.0175	600.3	1.04	1080	676.9	727.0	0.93
		80 x 80 x 4	0.99	0.0190	607.4	1.04	1124	712.1	714.0	1.00
		80 x 80 x 4	0.99	0.0191	607.9	1.04	1125	713.4	711.0	1.00
		80 x 80 x 4	0.71	0.0212	355.5	1.00	1105	392.9	309.0	1.27
		80 x 80 x 4	0.73	0.0198	352.3	1.00	1080	380.5	335.0	1.14
		100 x 100 x 2	2.18	0.0027	318.1	0.86	743	203.5	197.0	1.03
		100 x 100 x 2	2.17	0.0028	323.7	0.86	739	206.2	187.0	1.10
		100 x 100 x 3	1.44	0.0061	427.7	1.02	1101	478.1	489.0	0.98
		100 x 100 x 3	1.46	0.0060	426.5	1.02	1089	471.5	496.0	0.95
		100 x 100 x 4	1.16	0.0116	542.6	1.03	1431	803.4	779.0	1.03
		100 x 100 x 4	1.16	0.0116	542.6	1.03	1426	800.6	774.0	1.03
		100 x 100 x 6	0.77	0.0329	679.5	1.05	2147	1530.0	1513.0	1.01
		100 x 100 x 6	0.78	0.0325	678.4	1.05	2153	1531.3	1507.0	1.02
		100 x 100 x 8	0.46	0.0779	542.7	1.07	2785	1615.5	1630.0	0.99
		100 x 100 x 8	0.46	0.0783	543.2	1.07	2781	1614.8	1797.0	0.90
[17]	RHS 1.4301	150 x 100 x 3	1.98	0.0027	274.2	0.9	1397	344.7	372.0	0.93
		150 x 100 x 6	1.03	0.0119	433.1	1.04	2683	1208.5	1292.0	0.94
Gardner [1]	RHS 1.4301	60 x 40 x 4	0.72	0.0395	692.6	1.05	675	493.2	492.0	1.00
		60 x 40 x 4	0.72	0.0393	692.0	1.05	675	492.7	497.0	0.99
		120 x 80 x 3	1.86	0.0044	436.5	0.93	1109	449.1	452.0	0.99
		120 x 80 x 3	1.88	0.0043	433.0	0.93	1100	441.0	447.0	0.99
		120 x 80 x 6	0.96	0.0201	624.2	1.06	2107	1388.0	1459.0	0.95
		120 x 80 x 6	0.96	0.0201	624.2	1.06	2108	1388.6	1465.0	0.95
		150 x 100 x 4	1.53	0.0048	346.2	0.98	1799	611.3	660.0	0.93
		150 x 100 x 4	1.52	0.0048	346.2	0.98	1805	613.7	659.0	0.93
		100 x 50 x 2	2.24	0.0026	312.4	0.86	529	142.0	182.0	0.78
		100 x 50 x 2	2.26	0.0026	312.4	0.86	529	141.7	181.0	0.78
		100 x 50 x 3	1.60	0.0061	506.0	0.97	811	398.1	407.0	0.98
		100 x 50 x 3	1.60	0.0061	506.0	0.97	811	398.1	415.0	0.96
		100 x 50 x 4	1.19	0.0109	540.1	1.04	1026	576.3	626.0	0.92
		100 x 50 x 4	1.21	0.0105	537.3	1.04	1014	566.5	627.0	0.90
		100 x 50 x 6	0.77	0.0330	711.5	1.07	1558	1181.5	1217.0	0.97
		100 x 50 x 6	0.77	0.0332	712.1	1.07	1559	1182.4	1217.0	0.97

Table 7 Summary of the comparison between the proposed method and test results.

Angle		Channel		Lip. channel		H section		SHS		RHS	
avg.	s. dev.	avg.	s. dev.	avg.	s. dev.	avg.	s. dev.	avg.	s. dev.	avg.	s. dev.
1.00	0.11	1.00	0.13	0.98	0.07	0.98	0.11	1.07	0.15	0.94	0.06

Table 7 (contd.) Summary of the comparison between the proposed method and test results.

Open sections		Hollow sections		All Sections	
avg.	s. dev.	avg.	s. dev.	avg.	s. dev.
0.99	0.10	1.02	0.14	1.00	0.12

Table 8 Comparison between FE predictions and test results for the SHS Grade 1.4318 tested by Kuwamura [11]

Nominal size	Test F_u kN	FE F_u kN	Pred F_u kN	Pred F_u /Test F_u	Pred F_u /FE F_u
50 x 50 x 3	377	407	388	1.03	0.95
75 x 75 x 3	459	549	553	1.20	1.01
100 x 100 x 3	469	580	633	1.35	1.09
125 x 125 x 3	480	574	687	1.43	1.20
150 x 150 x 3	483	592	694	1.44	1.17
200 x 200 x 3	512	655	646	1.26	0.99
Average				1.29	1.07
Standard Deviation				0.16	0.10

Figure 1 Dimension of compression elements used in the present study.

Figure 2 Cross-section deformation capacity versus cross-section slenderness for all sections.

Figure 3 Mean design curve to determine cross-section deformation capacity.

Figure 4 Comparison between predicted compressive strengths to the test results.

Figure 5 Behaviour of slender and stocky stub columns showing differences with coupon.

Figure 6 Comparison between corrected predictions and test results.