Structural performance of stainless steel circular hollow sections under combined axial load and bending – Part 1: Experiments and numerical modelling

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Keywords: Austenitic stainless steel; Cold-formed; Combined loading tests; Cross-sectional behaviour; Finite element analysis; Numerical modelling; Stub column tests

Abstract

A comprehensive experimental and numerical investigation into the structural performance of stainless steel circular hollow sections (CHS) under combined compression and bending moment has been performed and is fully reported in the present paper and its companion paper. The experimental programme employed four CHS sizes made of austenitic stainless steel, and included material tensile coupon tests, four stub column tests and twenty combined loading tests. The initial loading eccentricities for the combined loading tests were varied to provide a wide range of bending moment-to-axial load ratios. In conjunction with the testing programme, a numerical modelling programme was performed to simulate the experiments. The developed FE models were shown to be capable of replicating the key test results, full

experimental curves including the post-ultimate range and deformed failure modes. Upon validation of the FE models, a series of parametric studies were conducted in the companion paper, aiming at extending the current test data pool over a range of cross-section sizes and combinations of loading. The experimental data, together with the generated parametric study results, were analysed and employed to evaluate the applicability of the codified provisions given in the European code, American specification and Australia/New Zealand standard for design of CHS under combined loading. Improved design rules were also sought through extension of the deformation-based continuous strength method (CSM) to the case of stainless steel CHS under combined loading.

1. Introduction

In recent years, increasing emphasis is being placed on the whole-life performance of structures, rather than simply the initial material cost. Stainless steel, although being initially more expensive than structural carbon steel, has excellent corrosion resistance, and reduced inspection and maintenance requirements, and thus can become more competitive in terms of material selection when considered on a life-cycle basis [1]. In addition to the excellent durability, the attractive aesthetic appearance, favourable mechanical properties and good ductility have also led to the increased use of stainless steels in structural applications. The behaviour and design of stainless steel circular hollow sections (CHS) under combined loading, which has been largely unexplored to date, is the focus of the present study. A brief review of the previous relevant studies is described below. Stub column [2–12] and four-point bending [4,13,14] tests have been conducted on stainless steel CHS of varying cross-section classes to investigate their cross-sectional load-carrying and deformation capacities under pure compression and bending. New slenderness limits for the classification of CHS

were proposed by Gardner et al. [15], which lead to more accurate section capacity predictions than with current codified limits. Considering that the general approach in structural stainless steel codes is to limit the design stress to the 0.2% proof stress and ignore the pronounced strain hardening in the determination of cross-section resistances, a deformation-based design approach called the continuous strength method (CSM) [16–21] was developed to allow a rational exploitation of strain hardening; the CSM has been shown to offer substantially improved predictions of cross-section compression and bending resistances for CHS over current codified design methods. Rasmussen and Hancock [2], Talja [3] and Burgan et al. [4] carried out a series of tests on stainless steel CHS columns and beam-columns to study their global buckling behaviour, while the structural performance of concrete-filled stainless steel CHS stub columns and long columns was studied by Lam and Gardner [11] and Uy et al. [12]. However, to date, there have been no investigations into the cross-sectional behaviour of stainless steel circular hollow sections subjected to combined axial load and bending moment, and this is therefore the topic of the present study.

This paper and its companion paper [22] describe a comprehensive experimental and numerical study of stainless steel circular hollow sections under combined loading. The present paper includes a testing programme on material tensile coupons, and concentrically and eccentrically loaded stub columns, followed by a numerical study, where the models are firstly validated against the performed experiments. Upon validation of the finite element models, a series of parametric studies is carried out and reported in the companion paper [22]. The experimentally and numerically derived data are initially utilised to evaluate the accuracy of the current codified design provisions in the European code EN 1993-1-4 [23], American specification SEI/ASCE-8 [24] and Australia/New Zealand standard AS/NZS 4673 [25], and

then used to develop improved design rules through extension of the deformation-based continuous strength method (CSM) to the case of CHS under combined loading.

2. Experimental investigation

2.1 General

An experimental programme was conducted to study the cross-sectional response of cold-formed stainless steel circular hollow sections under combined axial load and bending moment. Four cross-section sizes were employed in the testing: CHS 60.5×2.8, CHS 76.3×3, CHS 114.3×3 and CHS 139.4×3, all of grade EN 1.4301 (AISI 304) austenitic stainless steel. The first two cross-sections are defined as Class 1 under pure compression, while the latter two are Class 2 and Class 3, respectively, according to the slenderness limits of EN 1993-1-4 [23]. Overall, the experimental programme comprised material tensile coupon tests, four concentrically loaded stub column tests, and twenty eccentrically loaded stub column tests (combined loading tests). For each type of test, the employed test setup, experimental procedures and the obtained test results are fully described and reported in the following sections.

2.2 Material testing

Prior to structural testing, tensile coupon tests were carried out to determine the material stress–strain response of the tested cross-sections. For each cross-section, two longitudinal coupons, extracted at 90 degrees from the weld (see Fig. 1), were tested. The coupons were dimensioned and machined in accordance with the requirements of the Australian standard

AS 1391 [26] and the American standard ASTM E8M [27]. The tensile coupons were 4 mm in width with a 25 mm gauge length. Two holes with a diameter of 8.5 mm were drilled at a distance of 15 mm from both ends of the coupons, and a pair of steel rods was inserted into the holes to apply force to the coupons in the material tensile coupon tests, as shown in Fig. 2. Displacement control was used to drive an MTS testing machine at the loading rates of 0.05 mm/min and 0.2 mm/min up to and beyond the 0.2% proof stress, respectively. The resulting strain rate of the necked part of the coupon conformed to the requirements of AS 1391 [26] and ASTM E8M [27]. The instrumentation consisted of an extensometer mounted onto the specimens by three-point contact knife edges to determine the elongation of the coupon over the 25 mm gauge length, and two strain gauges affixed to the mid-height of the coupons to measure the longitudinal strains. The strain gauge readings were initially employed to determine the Young's modulus and then used to calibrate the strain measurements from the extensometer. Table 1 summarises the average measured material properties, including the Young's modulus E , the 0.2% proof stress $\sigma_{0.2}$, the 1.0% proof stress $\sigma_{1.0}$, the ultimate tensile strength σ_u , the strain at the ultimate tensile stress ε_u , the plastic strain at fracture measured over the standard gauge length (25 mm) ε_f , and the strain hardening exponents n , $n'_{0.2,1.0}$ and $n'_{0.2,u}$, as used in the compound Ramberg–Osgood (R–O) material model [28–32].

2.3 Stub column tests

For each circular hollow cross-section, a concentric stub column test was carried out to determine the cross-section load-carrying and deformation capacities under pure compression. The axial cross-sectional compressive capacity of each concentrically loaded stub column specimen represents the upper limit capacity of the corresponding eccentrically loaded stub column specimens. The nominal length for each specimen complied with the guidelines of

Ziemian [33], and is deemed short enough to prevent global buckling, but still long enough to contain a representative pattern of local geometric imperfections and residual stresses. For each stub column specimen, the measured geometric properties, including the member length L , the outer diameter D , the material thickness t and the cross-section area A , are reported in Table 2.

The ends of each stub column were firstly milled flat and square and then clamped by steel loops, as shown in Fig. 3, in order to eliminate any possibility of local failure at the ends due to any out-of-flatness of the end surfaces. An INSTRON 5000 kN hydraulic testing machine with fixed end platens was employed for the stub column testing, which was performed at a constant speed of 0.2 mm/min. Fig. 3 shows the test setup, consisting of three Linear Variable Displacement Transducers (LVDT) to determine the end shortening and three strain gauges, attached to the specimen at mid-height, to measure the axial strains. The strain gauge readings were used to eliminate the elastic deformation of the end platens of the test machine from the end shortening measurements of the LVDTs and determine the true end shortening values, following the procedures recommended in [34]. The modified true load–end shortening curves are shown in Fig. 4, while a summary of the key experimental results, including the ultimate load N_u and the corresponding end shortening δ_u at the ultimate load is reported in Table 3. All the stub columns failed by inelastic local buckling with an elephant foot pattern, a typical example of which is shown in Fig. 5 for specimen CHS 60.5×2.8.

2.4 Combined loading tests

For each of the four studied cross-sections, five combined loading tests were conducted under varying initial loading eccentricities to investigate the local buckling behaviour of stainless

steel circular hollow sections under combined axial compressive load and bending moment. The nominal initial loading eccentricities ranged from 5 mm to 110 mm, and thus resulted in a range of proportions of bending moment-to-axial load being considered. Measurements of the geometric dimensions of the specimens were conducted before the 25.4 mm end plates were welded to the member ends, and are reported in Table 4, where the nominal initial loading eccentricities e_n are also provided. Note that the nominal length of each combined loading specimen is equal to that of the corresponding stub column specimen.

Figs 6(a) and 6(b) show a photograph and schematic diagram of the combined loading test setup. The combined loading tests were conducted using an AVERY 1000 kN hydraulic testing machine with pin-ended bearings at both ends. Each pin-ended bearing is made up of a wedge plate containing a knife-edge wedge, and a pit plate with a V-shaped groove, as depicted in Figs 6(a) and 6(b). The specimens were bolted to the wedge plates, which had slotted holes to allow adjustment of the relative position between the centrelines of the specimen and the knife-edge in order to obtain the nominal initial loading eccentricities. The specimens, together with the wedge plates, were then positioned in the testing machine between the two pit plates. To eliminate any possible gap between the knife-edges and the V-grooved pit plates, the bottom pit plate, seated on a special bearing, was initially free to rotate in any direction and a small alignment load of 2 kN was then applied. At this point, the bottom pit plate was restrained against rotation and twist deformations by tightening the vertical and horizontal bolts. During the combined loading tests, two LVDTs, located at one end of the test specimen, were used to measure the end rotation, one additional LVDT, placed at the mid-height of the specimen, was employed to determine the lateral deflection and thus the second order bending moment, and two strain gauges, affixed to the extreme fibres of the section at mid-height in the buckling direction, were utilized to capture the longitudinal

strains, which were employed to determine the actual initial loading eccentricities, as discussed later. Note that the actual initial eccentricities were also measured directly using a Vernier; the values obtained were close to those calculated from the strain gauges, but the eccentricities obtained based on the strain gauge readings are considered to be more accurate [35–38] and have been used throughout this study. The calculated (actual) initial eccentricities e_0 for the combined loading tests are reported in Table 5, while the determination procedure is described as follows. In each combined loading test, the measured longitudinal strains are made up of two components: (i) strains due to the applied axial compressive load $\varepsilon_c = (\varepsilon_{max} + \varepsilon_{min})/2$, and (ii) strains due to the corresponding bending moment $\varepsilon_b = (\varepsilon_{max} - \varepsilon_{min})/2$, where ε_{max} and ε_{min} are the strain gauge values of the maximum compressive fibre and the maximum tensile (or the minimum compressive, in some cases) fibre, respectively. The actual bending moment (the sum of the first and second order bending moments) at mid-height is equal to $M = EI\kappa$, where I is the second moment of area and κ is the curvature at mid-height equal to $\varepsilon_b / 0.5D$. The actual initial eccentricity is then evaluated as $e_0 = (EI\kappa / N - \Delta)$, where N is the applied load and Δ is the lateral deflection at mid-height, as measured by the LVDT. The final expression for the calculation of the initial loading eccentricity about the axis of buckling is defined by Eq. (1). Note that the initial eccentricity was determined as the average calculated value during the early stages of loading (the authors suggest using no more than 15% of the ultimate load), where the structural behaviour was very close to linear elastic.

$$e_0 = \frac{EI(\varepsilon_{max} - \varepsilon_{min})}{DN} - \Delta \quad (1)$$

All the combined loading (eccentrically-loaded stub column) tests were performed under displacement control at a constant speed of 0.2 mm/min. Table 5 reports the key experimental

details and results, including the nominal e_n and actual (calculated) e_0 initial loading eccentricities, the ultimate load N_u , the mid-height lateral deflection at the ultimate load e' , the end rotation at the ultimate load ϕ_u , and the failure moment M_u , determined as a product of the ultimate load N_u and the sum of the calculated initial loading eccentricity e_0 and mid-height lateral deflection at the ultimate load e' . The full experimental load–end rotation curves for the four series of tests are depicted in Figs 7(a)–7(d), while typical local buckling failure modes are shown in Figs 8 and 9.

3. Numerical modelling

3.1 General

In parallel with the laboratory testing, a numerical modelling programme, using the nonlinear finite element analysis package ABAQUS [39], was performed. The initial aims of the numerical study were to replicate the full load–deformation histories, key results and failure modes obtained from the tests, and to assess the sensitivity of the FE models to various levels of local imperfection. Upon validation of the FE models, a series of parametric studies, as reported in the companion paper [22], were carried out to generate further structural performance data over a wide range of cross-section slenderness and combinations of loading.

3.2 Basic modelling assumptions

Having been used successfully in previous numerical studies of thin-walled structures [37,38,40–47], the four-noded doubly curved shell element with reduced integration and accounting for finite membrane strains, S4R [39], was employed in the present numerical

investigation for the modelling of the circular hollow sections. A uniform mesh of size $t \times t$ along the circumferential and longitudinal directions of the sections was assigned to the whole model; the mesh size was fine enough to yield accurate results, but still remained computational efficiency. Since the experimental failure modes of the CHS stub columns and combined loading specimens were symmetric with respect to the mid-height plane and the plane perpendicular to the buckling axis, only half of the cross-section and specimen length were modelled, and suitable symmetry boundary conditions were applied.

ABAQUS requires the material properties to be specified in the format of true stress and log plastic strain; hence, the measured engineering stress–strain curves, represented by the two-stage Ramberg–Osgood material model [28–32], were converted into true stress–log plastic strain curves, according to Eq. (2) and Eq. (3), in which σ_{true} is the true stress, ε_{ln}^{pl} is the logarithmic plastic strain, and σ_{nom} and ε_{nom} are the engineering stress and strain, respectively.

$$\sigma_{true} = \sigma_{nom} (1 + \varepsilon_{nom}) \quad (2)$$

$$\varepsilon_{ln}^{pl} = \ln(1 + \varepsilon_{nom}) - \frac{\sigma_{true}}{E} \quad (3)$$

The tested stainless steel circular hollow sections were fabricated by cold-rolling flat metal sheet material into a circular tube and then seam-welding it closed. Thus, two types of residual stresses – through-thickness residual stresses arising from non-uniform plastic deformation during cold-forming and membrane residual stresses from welding, were introduced into the specimen during the production process and therefore would have existed in the sections in their unloaded state. The general influence of residual stresses on structural members is to cause premature yielding and loss of stiffness, resulting in reduced ultimate

load-carrying capacity. Previous researchers [2,48–50] have carried out careful residual stress measurements on cold-formed stainless steel tubes and concluded that the magnitude of the membrane residual stresses was very small compared to that of the bending residual stresses and thus the influence of the membrane residual stresses on the structural behaviour of these members was considered to be negligible. The bending residual stresses, which are evidenced by the longitudinal curvature of the tensile coupons when they were extracted from the structural sections, are approximately reintroduced during tensile testing as the coupons are returned to their straight configuration under the application of tensile loading. Thus, the effect of the through-thickness bending residual stresses that exist in the finished tubes may be considered to be inherently present in the measured material properties. Explicit incorporation of both the membrane and through-thickness bending residual stresses into the developed numerical models was therefore deemed unnecessary.

The end section boundary conditions were set as follows: For each stub column FE model, the end section was coupled to a reference point, where all degrees of freedom were restrained except for longitudinal translation; this end section boundary condition simulated the fixed boundary condition employed in the stub column tests. Regarding the combined loading FE models, all degrees of freedom for the nodes of the loaded end section were coupled to an eccentric reference point, only allowing longitudinal translation and rotation about the axis of buckling, to simulate the pin-ended boundary conditions used in the combined loading tests. The eccentricity was equal to the corresponding value employed in the tests. In addition, the eccentric reference point was offset longitudinally from the loaded end section by 87.4 mm, which is equal to the distance from the specimen end to the knife-edge, in accordance with the actual knife-edge arrangement, used in the tests.

Initial local geometric imperfections, which are introduced into thin-walled structural members primarily during the fabrication process, can significantly influence the development of local buckling, the load level at which plasticity initiates, the ultimate load-carrying capacity and the post-ultimate response [47]. It is therefore important and necessary to include suitable geometric imperfection patterns and amplitudes into the FE models, in order to accurately replicate the observed experimental load–deformation histories, local buckling failure modes and key test results. Similarly to previous numerical studies [37,38,40–47], the initial local geometric imperfection pattern along the member length was taken as the lowest local buckling mode shape under the considered loading condition, which generally represents the most unfavourable imperfection pattern; this was determined by means of a prior elastic eigenvalue buckling analysis [39]. Five imperfection amplitudes, defined as the fractions of the cross-section thickness ($t/10$, $t/20$, $t/50$, $t/100$ and $t/500$), were used to factor the imperfection pattern, in order to investigate the sensitivity of the FE models to various incorporated imperfection levels and seek the most suitable imperfection amplitude to be used in the parametric studies. Upon incorporation of the initial geometric imperfections into the FE models, geometrically and materially nonlinear analyses were carried out, using the modified Riks method [39] to trace the full load–deformation histories of the numerical models, including the post-ultimate path.

3.3 Validation of the numerical models

The accuracy of the FE models was evaluated by comparing the key results (i.e. ultimate load and deformation at the ultimate load), full load-deformation curves and local buckling failure modes obtained from tests with those derived from the numerical simulations. Tables 6 and 7 report the ratios of numerical to experimental ultimate loads and deformation parameters at failure, respectively, for various imperfection levels. It may be observed that the numerical

failure loads were well predicted for all five considered local imperfection amplitudes, and thus indicated the relative insensitivity of the models to the changes in imperfection magnitude. In contrast to the failure load prediction, the corresponding numerical deformation at the failure load (end-shortening δ_u for the stub column FE models and end rotation ϕ_u for the combined loading FE models) were sensitive to the incorporated imperfection amplitudes, with the average ratio of numerical to experimental deformation varying by a factor of two between the largest ($t/10$) and the smallest ($t/500$) imperfection values. The best agreement between the test and FE results was generally achieved when the imperfection amplitude of $t/100$ was employed in the numerical model, resulting in safe, accurate and consistent predictions of both ultimate loads and deformations.

Comparisons between the experimental and numerical load–deformation curves for typical concentrically and eccentrically loaded stub columns are showed in Figs 10 and 11, respectively, where the numerical load–deformation curves accurately may be seen to replicate the initial stiffness, the general shape and the post-ultimate response of the experimental curves. Good agreement between the test and FE local buckling failure modes is also obtained, as displayed in Figs 5, 8 and 9. In summary, the finite element models are capable of predicting the key test results, replicating the full experimental load–deformation histories and capturing the observed failure modes. The models are therefore considered to be validated and suitable for performing parametric studies.

4. Conclusions

An experimental programme on cold-formed austenitic stainless steel circular hollow sections subjected to combined axial compressive load and bending moment has been carried out and

presented in this paper. A total of eight material tensile coupon tests, four concentrically loaded stub column tests and twenty eccentrically loaded stub column tests were carried out. Various initial loading eccentricities were employed in the combined loading tests, resulting in a range of combinations of loading being considered. The test setup, experimental procedures, key results (i.e. ultimate load and deformation at the ultimate load), load–deformation curves and failure modes for each type of test have been fully reported. The experimental results were then utilized in the numerical simulation programme to validate finite element models. The developed FE models were shown to be capable of replicating the test results, load–deformation histories and local buckling failure modes, and are therefore considered to be suitable for conducting parametric studies in the companion paper [22]. All the experimentally and numerically derived data are used in the companion paper [22] to assess the applicability of the current codified design provisions for stainless steel circular hollow sections under combined loading and to develop more efficient design rules.

Acknowledgements

The authors are grateful to the Joint PhD Scholarship Programme from Imperial College London and the University of Hong Kong for its financial support and to Mr Manlai Wong from the University of Hong Kong for his contribution to the experimental investigations.

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Fig. 1. Locations of tensile coupons in the cross-section.

Fig. 2. Setup of material tensile coupon tests.

Fig. 3. Stub column test setup.

Fig. 4. Load–end shortening curves for stub column tests.

Fig. 5. Experimental and numerical failure modes for stub column specimen CHS 60.5×2.8.

(a) Experimental setup.

(b) Schematic diagram of the test setup.

Fig. 6. Beam-column test configuration.

(a) Test curves for CHS 60.5×2.8.

(b) Test curves for CHS 76.3×3.

(c) Test curves for CHS 114.3×3.

(d) Test curves for CHS 139.4×3.

Fig. 7. Load–end rotation curves for combined loading tests.

Fig. 8. Experimental and numerical failure modes for combined loading specimen CHS 76.3×3-2C.

Fig. 9. Experimental and numerical failure modes for combined loading specimen CHS 114.3×3-3E.

Fig. 10. Experimental and numerical load–end shortening curves for stub column specimen CHS 139.4×3.

(a) CHS 76.3x3-2C.

(b) CHS 114.3x3-3E.

Fig. 11. Experimental and numerical load–end rotation curves for typical combined loading specimens.

Table 1 Summary of key measured material properties from the tensile coupons.

Cross-section	E (GPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{1.0}$ (MPa)	σ_u (MPa)	ε_u (%)	ε_f (%)	R-O coefficient		
							n	$n'_{0.2,1.0}$	$n'_{0.2,u}$
CHS 60.5×2.8	190	355	396	780	47	55	5.3	2.4	1.9
CHS 76.3×3	195	302	347	784	48	56	7.3	2.0	1.9
CHS 114.3×3	187	290	324	799	45	53	7.8	1.7	1.6
CHS 139.4×3	188	323	361	757	52	60	4.9	2.2	1.8

Table 2 Measured geometric dimensions of stub column specimens.

Cross-section	L	D	t	A
	(mm)	(mm)	(mm)	(mm ²)
CHS 60.5×2.8	200.2	60.40	2.78	503.2
CHS 76.3×3	240.0	76.42	2.98	687.5
CHS 114.3×3	360.1	114.52	2.89	1013.5
CHS 139.4×3	434.8	139.80	2.92	1255.7

Table 3 Summary of test results for stub columns.

Cross-section	Ultimate load N_u	End shortening at ultimate load δ_u
	(kN)	(mm)
CHS 60.5×2.8	283.6	15.8
CHS 76.3×3	329.5	15.1
CHS 114.3×3	382.7	9.8
CHS 139.4×3	456.3	8.4

Table 4 Nominal load eccentricities e_n and measured dimensions of specimens under combined loading.

Cross-section	Specimen ID	e_n (mm)	L (mm)	D (mm)	t (mm)
CHS 60.5×2.8	1A	5.0	200.0	60.44	2.79
	1B	15.0	200.1	60.39	2.79
	1C	30.0	199.8	60.35	2.78
	1D	50.0	199.9	60.40	2.79
	1E	75.0	199.9	60.40	2.81
CHS 76.3×3	2A	10.0	240.1	76.42	2.97
	2B	25.0	240.3	76.40	2.94
	2C	45.0	240.0	76.34	2.96
	2D	70.0	240.3	76.32	2.97
	2E	100.0	240.2	76.40	2.99
CHS 114.3×3	3A	10.0	360.0	114.56	2.89
	3B	25.0	359.7	114.50	2.93
	3C	50.0	359.8	114.62	2.93
	3D	60.0	360.0	114.60	2.91
	3E	80.0	360.1	114.53	2.90
CHS 139.4×3	4A	5.0	434.8	139.78	2.92
	4B	20.0	435.0	139.81	2.92
	4C	40.0	435.0	139.75	2.91
	4D	80.0	434.8	139.75	2.92
	4E	110.0	434.6	139.80	2.92

Table 5 Summary of CHS combined loading test results.

Cross-section	Specimen ID	e_n (mm)	e_0 (mm)	N_u (kN)	e' (mm)	M_u (kNm)	ϕ_u (deg)
CHS 60.5×2.8	1A	5.0	5.6	144.4	6.0	1.68	2.42
	1B	15.0	15.2	111.2	6.9	2.46	2.87
	1C	30.0	30.0	78.0	9.2	3.06	4.02
	1D	50.0	51.7	55.8	9.3	3.40	4.14
	1E	75.0	75.2	40.5	14.6	3.64	5.69
CHS 76.3×3	2A	10.0	9.4	181.6	8.8	3.31	3.94
	2B	25.0	25.5	128.1	9.8	4.52	4.06
	2C	45.0	44.7	94.2	11.8	5.32	5.12
	2D	70.0	71.1	65.2	15.7	5.66	5.30
	2E	100.0	100.0	51.0	17.0	5.97	5.99
CHS 114.3×3	3A	10.0	9.7	266.8	7.4	4.56	2.60
	3B	25.0	24.4	214.5	6.9	6.71	2.45
	3C	50.0	49.6	157.1	7.4	8.95	2.83
	3D ^a	60.0	–	–	–	–	–
	3E	80.0	80.0	118.1	8.0	10.39	3.18
CHS 139.4×3	4A	5.0	5.8	378.9	5.9	4.43	1.75
	4B	20.0	19.2	312.5	5.6	7.75	1.76
	4C	40.0	39.5	246.5	5.4	11.07	1.78
	4D	80.0	80.0	169.8	5.9	14.59	2.24
	4E	110.0	110.0	134.5	10.1	16.15	2.27

Note:

a. Test was interrupted near peak load – experimental results could not be obtained.

Table 6 Comparison of the test failure loads with FE failure loads for varying imperfection amplitudes.

(a) Stub column tests.

Cross-section	FE N_u /Test N_u				
	$t/10$	$t/20$	$t/50$	$t/100$	$t/500$
CHS 60.5×2.8	0.89	0.90	0.90	0.92	0.92
CHS 76.3×3	0.91	0.92	0.92	0.93	0.93
CHS 114.3×3	0.93	0.93	0.94	0.94	0.94
CHS 139.4×3	0.99	1.00	1.00	1.00	1.00
Mean	0.93	0.94	0.94	0.95	0.95
COV	0.05	0.05	0.05	0.04	0.04

(b) Combined loading tests.

Cross-section	Specimen ID	FE N_u /Test N_u					
		e_0	$t/10$	$t/20$	$t/50$	$t/100$	$t/500$
CHS 60.5×2.8	1A	5.6	0.98	1.00	1.00	1.00	1.00
	1B	15.2	0.98	0.99	1.00	1.00	1.00
	1C	30.0	1.00	1.02	1.03	1.03	1.03
	1D	51.7	0.96	0.98	0.98	0.98	0.98
	1E	75.2	0.98	0.99	1.00	1.01	1.01
CHS 76.3×3	2A	9.4	0.93	0.95	0.97	0.97	0.98
	2B	25.5	0.95	0.97	0.99	0.99	1.01
	2C	44.7	0.94	0.96	0.98	0.98	1.00
	2D	71.1	0.95	0.97	0.99	1.00	1.01
	2E	100.0	0.96	0.98	1.00	1.01	1.03
CHS 114.3×3	3A	9.7	0.94	0.97	0.99	1.01	1.02
	3B	24.4	0.94	0.97	0.99	1.01	1.02
	3C	49.6	0.93	0.96	0.99	1.00	1.01
	3D ^a	—	—	—	—	—	—
	3E	80.0	0.93	0.96	0.99	1.00	1.01
CHS 139.4×3	4A	5.8	0.94	0.97	0.99	1.00	1.02
	4B	19.2	0.94	0.97	0.99	1.01	1.03
	4C	39.5	0.93	0.96	0.99	1.00	1.03
	4D	80.0	0.94	0.98	1.01	1.02	1.05
	4E	110.0	0.95	0.99	1.02	1.03	1.06
Mean			0.95	0.98	0.99	1.00	1.02
COV			0.02	0.02	0.01	0.01	0.02

Table 7 Comparison of the test ultimate deformation with FE ultimate deformation for varying imperfection amplitudes.

(a) Stub column tests.

Cross-section	FE δ_u / Test δ_u				
	$t/10$	$t/20$	$t/50$	$t/100$	$t/500$
CHS 60.5×2.8	0.63	0.69	0.72	0.82	0.85
CHS 76.3×3	0.67	0.74	0.79	0.85	0.85
CHS 114.3×3	0.79	0.81	0.85	0.90	0.95
CHS 139.4×3	0.80	0.82	0.85	0.95	0.96
Mean	0.72	0.77	0.80	0.88	0.90
COV	0.12	0.08	0.08	0.06	0.07

(b) Combined loading tests.

Cross-section	Specimen ID	FE ϕ_u / Test ϕ_u					
		e_0	$t/10$	$t/20$	$t/50$	$t/100$	$t/500$
CHS 60.5×2.8	1A	5.6	0.68	0.83	0.90	0.93	0.90
	1B	15.2	0.78	0.90	0.96	0.97	0.98
	1C	30.0	0.63	0.75	0.83	0.82	0.85
	1D	51.7	0.76	0.89	1.00	1.02	1.01
	1E	75.2	0.54	0.65	0.77	0.79	0.81
CHS 76.3×3	2A	9.4	0.61	0.75	0.96	1.02	1.06
	2B	25.5	0.61	0.72	0.92	0.99	1.00
	2C	44.7	0.53	0.69	0.84	0.91	0.92
	2D	71.1	0.46	0.58	0.70	0.78	0.80
	2E	100.0	0.46	0.57	0.70	0.77	0.79
CHS 114.3×3	3A	9.7	0.40	0.54	0.75	0.87	1.01
	3B	24.4	0.48	0.64	0.88	1.02	1.08
	3C	49.6	0.49	0.62	0.87	1.01	1.06
	3D ^a	—	—	—	—	—	—
	3E	80.0	0.51	0.64	0.82	0.94	1.06
CHS 139.4×3	4A	5.8	0.44	0.61	0.84	0.97	1.10
	4B	19.2	0.43	0.53	0.70	0.81	0.89
	4C	39.5	0.51	0.62	0.82	0.91	0.99
	4D	80.0	0.52	0.59	0.80	0.90	0.95
	4E	110.0	0.57	0.68	0.87	0.99	1.06
Mean			0.55	0.67	0.84	0.92	0.96
COV			0.20	0.16	0.11	0.09	0.11