Experimental and numerical study of hot-rolled duplex stainless steel CHS columns

Keyang Ning, Lu Yang, Jie Wang, Peng Dai, Yinan Sun

Abstract: Stainless steel circular hollow section (CHS) members have been widely used in building structures because of their comparable strength to structural carbon steels, attractive appearance and excellent corrosion resistance. However, research on stainless steel CHS members has been limited to cold-formed members, whereas hot-rolled CHS columns have received less attention. To this end, the flexural buckling performance of hot-rolled duplex stainless steel CHS columns was investigated by a comprehensive experimental and numerical programme. A total of seven hot-rolled duplex stainless steel CHS columns covering two cross-sectional sizes with varying lengths have been tested under compression. Based on the test results, finite element (FE) models were developed and used in parametric studies to generate data points with a wider range of geometric dimensions. Comparing the test and FE results with current design guidance, it was found that the Chinese standard, CECS 410, and North American design guidance, AISC DG 27, underestimate significantly the flexural buckling resistance of such columns, while the design method in Eurocode 3: Part 1-4 might be unsafe in predicting the resistances for low slenderness values. New column buckling curves based on the Eurocode 3 and AISC DG 27 design formulae with improved accuracy and reduced scatters were also proposed and validated through careful reliability analysis.

Keywords: circular hollow section; stainless steel; hot-rolled; design method; flexural buckling

1. Introduction

Stainless steels have the advantages of comparable strength to structural carbon steels, excellent corrosion resistance, low life cycle cost and attractive appearance, all contributing towards their wide applicability in building structures [1]. In recent years, plenty of research work has been done on the flexural buckling performance of stainless steel columns, and fruitful research findings have been achieved. These include Ashraf et al. [2], Afshan et al.[3], Theofanous et al.[4,5], Huang and Young [6-8], Buchanan et al. [9], and He et al. [10], the results of which covered a range of cold-formed hollow sections (circular hollow section (CHS), oval hollow section (OHS), rectangular and square hollow sections (RHS and SHS)) and three material grades (austenitic, ferritic, and duplex). Based on the obtained experimental and numerical results, various existing design methods for cold-formed stainless steel structures have been evaluated and new design recommendations have been proposed. Research into stainless steel welded section members includes Yuan et al. [11,12], Yang et al. [13,14], Shameem et al. [15], Sun et al. [16], Gardner et al. [17] and Bu and Gardner [18], where test and FE studies on austenitic and duplex stainless steel built-up box-section and I-section columns were performed. Recently, Arthur et al. [19] carried out a comprehensive test and FE study on stainless steel hot-rolled angle section columns under axial compression, and updated the corresponding column buckling curves in EN 1993-1-4+A1 [20].

Among all the available research works on stainless steel members, the research on CHS columns is mainly limited to cold-formed members [2, 8, 9] and very little information can be found for the hot-rolled stainless steel CHS members. Compared to hot-rolled sections, cold-formed structures generally have smaller wall thicknesses and limited cross-section sizes, hence possessing limited load-carrying capacities. In this regard, hot-rolled members with relatively large wall thicknesses and cross-sectional areas may offer a better structural solution when higher load-carrying
capacities are required in design. The design of hot-rolled stainless steel CHS members refers to various design rules as offered by different design standards in the world [20-22]. The rationality of these design rules still needs to be verified by a sufficient amount of data. In particular, in the Chinese standard, CECS 410 [21], there is no buckling curve specified for the design of hot-rolled stainless steel CHS columns due to the lack of relevant test data.

To this end, a comprehensive experimental and numerical programme on the flexural buckling performance of hot-rolled duplex (grade 2205) stainless steel CHS columns has been performed and is reported in this paper. Seven column tests were conducted, and the test results were used to develop valid FE models. Then the valid FE models were employed for parametric studies to generate more data points with a wider range of geometric dimensions. According to the obtained experimental and numerical results, existing design methods in European standard, EN 1993-1-4+A1 [20], Chinese standard, CECS 410 [21], and North American design guidance, AISC DG 27 [22], were assessed. In addition, new flexural buckling curves, developed based on the current design formulations in these standards [20-22], were proposed to give more accurate predictions to the hot-rolled duplex stainless steel CHS columns.

2. Experimental programme

2.1 Specimen fabrication and material properties

A total of seven hot-rolled duplex (grade 2205) stainless steel CHS columns covering two cross-sectional sizes (114 × 6 and 219 × 6) with varying lengths were tested. The measured geometries of the specimens are shown in Table 1, where D is the average outer diameter, t is the average wall thickness of the cross-section, respectively, as denoted in Fig. 1, L represents the cut length of the
column, \( L_t \) represents the effective length taking into account of the height of the two knife edges (\( L_t = L + 340 \) mm) and \( \bar{\lambda} \) represents the non-dimensional slenderness of specimen. In the specimen label, 114 \( \times \) 6 and 219 \( \times \) 6 stand for the nominal cross-section sizes and the last number represents the nominal cut length (in mm) of the specimen.

\[ \]

**Fig.1** Geometric symbols of hot-rolled CHS

<table>
<thead>
<tr>
<th>Specimens</th>
<th>( D ) (mm)</th>
<th>( t ) (mm)</th>
<th>( L ) (mm)</th>
<th>( L_t ) (mm)</th>
<th>( \bar{\lambda} )</th>
<th>Section class</th>
</tr>
</thead>
<tbody>
<tr>
<td>114 ( \times ) 6-3000</td>
<td>113.9</td>
<td>5.98</td>
<td>3022</td>
<td>3362</td>
<td>1.51</td>
<td>1</td>
</tr>
<tr>
<td>114 ( \times ) 6-3500</td>
<td>114.9</td>
<td>6.44</td>
<td>3522</td>
<td>3862</td>
<td>1.73</td>
<td>1</td>
</tr>
<tr>
<td>114 ( \times ) 6-4000</td>
<td>114.5</td>
<td>6.28</td>
<td>4022</td>
<td>4362</td>
<td>1.96</td>
<td>1</td>
</tr>
<tr>
<td>114 ( \times ) 6-4500</td>
<td>114.4</td>
<td>6.09</td>
<td>4523</td>
<td>4863</td>
<td>2.18</td>
<td>1</td>
</tr>
<tr>
<td>219 ( \times ) 6-2500</td>
<td>219.7</td>
<td>6.34</td>
<td>2524</td>
<td>2864</td>
<td>0.63</td>
<td>3</td>
</tr>
<tr>
<td>219 ( \times ) 6-4000</td>
<td>220.5</td>
<td>7.08</td>
<td>4023</td>
<td>4363</td>
<td>0.96</td>
<td>3</td>
</tr>
<tr>
<td>219 ( \times ) 6-4500</td>
<td>220.3</td>
<td>6.88</td>
<td>4530</td>
<td>4870</td>
<td>1.07</td>
<td>3</td>
</tr>
</tbody>
</table>

The coupons for tensile material tests were cut directly from the reserved tubes that are in the same batch as the test columns. From each cross-section size, three tensile coupons (A, B and C) were extracted from the locations as indicated in Fig 2, resulting in a total of six tensile coupons. The tensile coupon tests were carried out on a Zwick/Roell Z100 loading jack with a maximum tonnage of 10t, following the procedure specified in GB/T 228.1-2010 [23]. The obtained stress-strain (\( \sigma-\varepsilon \)) curves from the tests are plotted in Fig. 3, and the important material properties, such as 0.2% proof stress (\( f_{0.2} \)), the Young’s modulus (\( E \)), the ultimate tensile strength (\( f_u \)), the strain hardening exponent (\( n \))
and the plastic strain at fracture ($\varepsilon_f$), are reported in Table 2

![Fig. 2 The sampling locations of the tensile coupons](image)

![Fig. 3 Measured full stress-strain curves](image)

**Table 2** Average material properties obtained from tensile coupon tests

<table>
<thead>
<tr>
<th>Coupons</th>
<th>$E$ (MPa)</th>
<th>$f_{0.2}$ (MPa)</th>
<th>$f_u$ (MPa)</th>
<th>$\varepsilon_f$ (%)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>114 × 6</td>
<td>207421</td>
<td>606.0</td>
<td>766.0</td>
<td>32.0</td>
<td>5.8</td>
</tr>
<tr>
<td>219 × 6</td>
<td>205678</td>
<td>560.0</td>
<td>800.0</td>
<td>38.7</td>
<td>4.3</td>
</tr>
</tbody>
</table>

2.2 Geometric imperfections

Since all test columns were designed to be susceptible to overall flexural buckling, only the global imperfections of the columns were measured. The measurement adopted the pull wire method, in which a thin wire was drawn longitudinally between the two ends of the test column and was pressed as closer as possible to the surfaces of the column ends. The thin wire is pressed as much as possible to fit the outer wall of the end of the column. The deviations of the wire to the tube surface at the quartering points were measured for four times and the maximum value was taken as the
imperfection values ($\delta_1$, $\delta_2$ and $\delta_3$) at these points, as shown in Fig. 4. The maximum value of $\delta_1$, $\delta_2$ and $\delta_3$ was reported as the global geometric imperfection ($\delta_0$) of the specimen, as summarised in Table 3. The loading eccentricity ($e$) of each specimen can be determined by $e = (e_b + e_t)/2$ [24], where $e_b$ and $e_t$ are the loading eccentricity of the top and bottom of the specimen respectively. The equivalent initial eccentricity ($e_{\text{eq}}$) approximately equal to $e$ plus $\delta_0$, is also reported in Table 3 for each specimen. It can be seen that the $e_{\text{eq}}$ values for all specimens are relatively small (below $L/1000$).

![Fig. 4 Global initial imperfection measurement](image)

### Table 3 Measured initial geometric imperfections

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Initial geometric imperfections (mm)</th>
<th>Loading eccentricity (mm)</th>
<th>$e_{\text{eq}}/L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>114 $\times$ 6-3000</td>
<td>$1.12$ $1.28$ $0.78$ $1.28$</td>
<td>$-0.081$ $0.270$</td>
<td>1/2183</td>
</tr>
<tr>
<td>114 $\times$ 6-3500</td>
<td>$0.99$ $0.43$ $1.78$ $1.78$</td>
<td>$-0.028$ $0.265$</td>
<td>1/1844</td>
</tr>
<tr>
<td>114 $\times$ 6-4000</td>
<td>$2.00$ $1.65$ $1.70$ $2.00$</td>
<td>$-0.068$ $0.324$</td>
<td>1/1880</td>
</tr>
<tr>
<td>114 $\times$ 6-4500</td>
<td>$2.00$ $0.87$ $1.32$ $2.00$</td>
<td>$-0.213$ $0.104$</td>
<td>1/2313</td>
</tr>
<tr>
<td>219 $\times$ 6-2500</td>
<td>$0.34$ $0.97$ $1.50$ $1.50$</td>
<td>$-0.370$ $-0.457$</td>
<td>1/2301</td>
</tr>
<tr>
<td>219 $\times$ 6-4000</td>
<td>$0.45$ $1.08$ $1.40$ $1.40$</td>
<td>$-0.286$ $0.560$</td>
<td>1/2602</td>
</tr>
<tr>
<td>219 $\times$ 6-4500</td>
<td>$1.55$ $2.56$ $1.27$ $2.56$</td>
<td>$-0.247$ $0.729$</td>
<td>1/1607</td>
</tr>
</tbody>
</table>

2.3 Flexural buckling tests

2.3.1 Loading setup and measurement arrangement

The WAW-2500 hydraulic universal testing machine, as shown in Fig. 5(a), was used to load the specimens. The specimens were pinned supported at the two ends using a pair of knife edges, which allow the rotation around the buckling axis.
During the tests, the load, deflection and strain development of the specimens were recorded.

The axial deformation, lateral displacement and end rotations of the columns were measured by nine linear variable displacement transducers (LVDTs), as depicted in Fig. 5(b). LVDT-1, 2, 7 and 8 were used to monitor the in-plane rotations of the column ends, LVDT-3 and 4 were located at the moving end of the loading jack to measure the axial deformation of the column, LVDT-5 and 6 were located at the middle height of the column to obtain the in-plane lateral displacement, and LVDT-9 was placed at the middle height cross-section to monitor the out-of-plane deflection. The load was read directly from the loading jack. The strain development during the tests was measured by three groups of four strain gauges arranged at the end (30mm away from the end-plate) and the mid-height cross-sections according to the arrangement shown in Fig. 6. The SG-1, 2, 3 and 4 and SG-9, 10, 11 and 12 were placed at the column ends and the SG-5, 6, 7 and 8 were placed at the middle height of the column.
2.3.2 Test results

The ultimate bearing capacities, $N_u$, of all specimens obtained in the tests are reported in Table 4. All the column specimens exhibited overall buckling instability before failure, and the typical failure mode is shown in Fig. 7. Fig. 8 shows the load versus lateral displacement at mid-height ($N-w$) curves of all the specimens. As expected, longer specimens displayed smaller ultimate resistances for the same cross-section sizes. In Fig. 8 (a), piecewise linear plateaus are found in the axial load versus lateral displacement curves for specimens 114 × 6-4000 and 114 × 6-4500. This is mainly due to the large tonnage of experimental loading equipment, which is not sensitive enough to the change of small force.

![Fig. 6 Layout of strain gauges](image)

![Fig. 7. Typical failure mode](image)
3. Numerical modelling

3.1 FE modelling technique

Following the experimental research, a numerical programme was performed to extend the test dataset. The FE software ANSYS was employed in the numerical study. The BEAM188 element, which has been successfully and extensively utilised in similar study to model tubular members under axial compression [13], was also adopted in the current study. The FE model and mesh are illustrated in Fig. 9, where the column was divided into 40 equal parts along the circumference of the section and 50 (for \(L < 4000\) mm) or 100 (for \(L > 4000\) mm) segments longitudinally. The boundary conditions were set as shown in Fig. 9, where the vertical movement of the loading end and the rotation about the buckling axes at both ends were released, and the other degrees of freedom at both ends were fixed.
Based on the measured stress-strain responses (Fig. 3) and the measured material properties reported in Table 2, a multi-linear kinematic hardening constitutive model was established and employed in the numerical modelling. Since all the experimental specimens displayed a global buckling failure mode, only global geometric imperfection was considered in the FE models. The shape of the first global eigenmode from Eigenvalue analysis (Fig. 10) was used to represent imperfection pattern, and the previously measured amplitudes of global geometric imperfections, as shown in Table 3, were input using the ‘UPGEOM’ command. The residual stresses were not considered in the FE models owing to the relatively low levels of membrane residual stresses as commonly found in hot-rolled members [25, 26]. The membrane residual stresses of hot-rolled sections are usually less than 10% of $f_{0.2}$ [27], and it has been proved in reference [28] that relatively low residual stress level has little effect on the overall performance and bearing capacity of stainless steel CHS columns. In similar studies on hot-rolled section columns [29, 30], residual stresses were also not particularly considered in the FE models. Providing the above arguments, the FE models in the current study did not include the residual stresses.
3.2 Validation

The FE results are compared with the corresponding test results in terms of the failure modes and the load-displacement relationships to verify the accuracy of the FE models. Fig. 11 shows typical comparisons between the failure modes achieved in the tests and the corresponding FE models, where agreement between the two has been achieved in both cases in Figs 11 (a) and (b). The FE and test load-lateral displacement curves of specimen 114 × 6-3000 and 219 × 6-4000 are compared in Figs. 12 (a) and (b), respectively. These selected examples demonstrate that the FE models can accurately capture the load-displacement responses as experienced by the test specimens.

The obtained test and FE ultimate load, $N_{u,test}$ and $N_{FE}$, are given in Table 4 for all the specimens. The mean FE-to-test ultimate load ratio $N_{FE}/N_{u,test} = 1.00$, confirming the validity of the developed FE models. In general, the developed FE models are shown to produce satisfactory predictions and can be employed in the subsequent parametric research.

![Comparison of test and FE failure modes](image)

(a) 114 × 6-3000  
(b) 219 × 6-4000

**Fig.11** Comparison of test and FE failure modes
Fig. 12 Comparison between FE and test load-lateral displacement curves

Table 4 Summary of test and FE results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( N_u\text{,test} ) (kN)</th>
<th>( N_{FE} ) (kN)</th>
<th>( N_{FE}/N_u\text{,test} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>114 × 6-3000</td>
<td>456.8</td>
<td>459.4</td>
<td>1.01</td>
</tr>
<tr>
<td>114 × 6-3500</td>
<td>402.0</td>
<td>406.4</td>
<td>1.01</td>
</tr>
<tr>
<td>114 × 6-4000</td>
<td>323.6</td>
<td>327.4</td>
<td>1.01</td>
</tr>
<tr>
<td>114 × 6-4500</td>
<td>214.8</td>
<td>216.9</td>
<td>1.01</td>
</tr>
<tr>
<td>219 × 6-2500</td>
<td>2134.1</td>
<td>2092.4</td>
<td>0.98</td>
</tr>
<tr>
<td>219 × 6-4000</td>
<td>1673.6</td>
<td>1670.0</td>
<td>1.01</td>
</tr>
<tr>
<td>219 × 6-4500</td>
<td>1430.4</td>
<td>1439.7</td>
<td>1.01</td>
</tr>
<tr>
<td>Mean</td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COV</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3 Parametric studies

Employing the validated FE models, parametric studies were carried out. Table 5 details the key variables in the parametric studies, in which nine cross-sections, covering three cross-sectional classes (Class 1, 2 and 3) [20] and three wall thicknesses \( t = 4, 6 \text{ and } 8 \text{ mm} \), varying in lengths were considered. In Table 5, \( D/t\epsilon^2 \) is the cross-sectional slenderness as defined in EN 1993-1-4+A1 [20], being \( \epsilon = \sqrt{235E_0/(210000\bar{f}_0.2)} \). It should be noted that only fully effective cross-sections (Class 1, 2 and 3) were considered in the parametric studies whereas the partially effective (Class 4) cross-sections which may experience premature local buckling failure are out of the scope of the current study. The input material parameters and stress-strain relationships were defined according to the averaged tensile coupon test results. The amplitude of global geometric imperfection in FE models is taken as \( L_i/1000 \). In total, there were 115 FE models generated in the parametric studies.
Table 5 Summary of specimen geometries in the parametric studies

<table>
<thead>
<tr>
<th>Grade</th>
<th>Section</th>
<th>D (mm)</th>
<th>t (mm)</th>
<th>D/t</th>
<th>D/tε^2</th>
<th>Class</th>
<th>λ</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duplex (2205;</td>
<td>64×4</td>
<td>64</td>
<td>4</td>
<td>16.0</td>
<td>40.4</td>
<td>1</td>
<td>0.20~2.0</td>
<td>11</td>
</tr>
<tr>
<td>EN 1.4462</td>
<td>95×4</td>
<td>95</td>
<td>4</td>
<td>23.8</td>
<td>59.9</td>
<td>2</td>
<td>0.20~2.0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>127×4</td>
<td>127</td>
<td>4</td>
<td>31.8</td>
<td>80.1</td>
<td>3</td>
<td>0.20~2.0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>95×6</td>
<td>95</td>
<td>6</td>
<td>15.8</td>
<td>39.9</td>
<td>1</td>
<td>0.10~2.3</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>152×6</td>
<td>152</td>
<td>6</td>
<td>25.3</td>
<td>63.9</td>
<td>2</td>
<td>0.20~2.0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>180×6</td>
<td>180</td>
<td>6</td>
<td>30.0</td>
<td>75.7</td>
<td>3</td>
<td>0.20~2.0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>114×8</td>
<td>114</td>
<td>8</td>
<td>14.3</td>
<td>35.9</td>
<td>1</td>
<td>0.20~2.0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>180×8</td>
<td>180</td>
<td>8</td>
<td>22.5</td>
<td>56.8</td>
<td>2</td>
<td>0.20~2.0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>245×8</td>
<td>245</td>
<td>8</td>
<td>30.6</td>
<td>77.2</td>
<td>3</td>
<td>0.20~2.0</td>
<td>11</td>
</tr>
</tbody>
</table>

4. Discussion and assessment of current design methods

Three design methods for hot-rolled duplex stainless steel CHS axial compression members, as included in the European standard, EN 1993-1-4+A1 [20], Chinese standard, CECS 410 [21], and North American design guidance, AISC DG 27 [22], were introduced and evaluated by means of the experimental and numerical results. Based on the assessment, modified design recommendations were proposed in Section 5.

4.1 EN 1993-1-4+A1

The design method for axial compression members in EN 1993-1-4+A1 is derived from the Perry Robertson buckling formula [31]. The resistance to flexural buckling (N_{b,Rd}) of members under axial compression is calculated according to Eqs (1-4) for Class 1, 2 and 3 cross-sections.

\[ N_{b,Rd} = \frac{\chi A_{f,0.2}}{\gamma_{M1}} \]  \hspace{1cm} (1)

\[ \chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} \leq 1 \]  \hspace{1cm} (2)

\[ \phi = 0.5 \left( 1 + \alpha \left( \frac{\lambda}{\lambda_0} + \lambda^2 \right) \right) \]  \hspace{1cm} (3)

\[ \lambda_0 = \sqrt{\frac{A_{f,0.2}}{N_{cr}}} \]  \hspace{1cm} (4)
where $A$ is the cross-sectional area, $\gamma_{M1}$ is the partial safety factor which is set to unity in the current study, and $\chi$ is the buckling reduction factor calculated according to Eqs (2-3) as a function of $\bar{\lambda}$ (as defined in Eq. (4), being $N_{cr}$ the Euler buckling load). In EN 1993-1-4+A1, an imperfection factor of $\alpha = 0.49$ and a limiting slenderness of $\lambda_0 = 0.4$ are adopted in the buckling curve for stainless steel hollow sections (welded and seamless).

4.2 CECS 410

In CECS 410, the design equation adopts the same format as in EN 1993-1-4+A1 (Eqs (1-4)) except that different values of $\alpha$ and $\lambda_0$ are used. In CECS 410, six buckling curves are given considering different fabrication processes and cross-section shapes (two for cold-formed and four for welded section members). The buckling curve of hot-rolled stainless steel CHS columns was not specifically defined in CECS 410 because of the lack of test data of such column. Therefore, for hot-rolled duplex stainless steel CHS columns, CECS 410 only gives conservative design recommendations ($\alpha$ and $\lambda_0$ are conservatively taken as 0.89 and 0.26, respectively.)

4.3 AISC DG 27

In AISC DG 27, a single column buckling curve is adopted to design stainless steel non-slender element compression members, as expressed in Eqs. (5-7), where $A_g$ is the gross area of the cross-section and the strength reduction due to flexural buckling is considered in the calculation of the critical stress $F_{cr}$.

\[
N_{h,Rd} = F_{cR}A_g
\]

\[
F_{cr} = \begin{cases} \frac{F_y}{F_{cR}} F_y & \text{for } \frac{F_y}{F_{cR}} \leq 1.44 \\ 0.50 F_y & \text{for } \frac{F_y}{F_{cR}} > 1.44 \end{cases}
\]

\[
F_{cr} = 0.531 F_y \quad \text{for } \frac{F_y}{F_{cR}} > 1.44
\]
4.4 Discussion and assessment

The design approaches for hot-rolled duplex stainless steel CHS axial compression members in the above three design standards were evaluated based on the test and FE results. Fig. 13 presents the three buckling curves with test and FE data, which are plotted in terms of the global slenderness $\bar{\lambda}$ versus the normalised resistance $N_u/Af_{0.2}$ (equivalent to buckling reduction factor). It can be seen from Fig.13 that for such columns, the EN 1993-1-4+A1 buckling curve provides more accurate strength predictions than the CECS 410 and AISC DG 27 curves, but is unsuitable for low slenderness values with overestimated predictions of the ultimate capacity. The CECS 410 curve underestimates significantly the resistances in the intermediate slenderness range ($\bar{\lambda} = 0.5$ to $1.5$) and the AISC DG 27 curve is increasingly conservative in the high slenderness range.

Numerical comparisons, in terms of the ratio between the obtained ultimate capacity, $N_u$, and the prediction, $N_{u,EC3}$ ($N_{u,CECS}$ and $N_{u,AISC}$), are summarised in Table 6. The mean value of $N_u/N_{u,EC3}$ equals to 1.04 and COV of 0.05, which confirms again the conclusion that the method in EN 1993-1-4+A1 provides the closest strength prediction among the three. The American approach gives the most conservative estimation of column capacities with the highest $N_u/N_{u,AISC}$ ratios (1.27) and COV values (0.18).
5. New flexural buckling curve proposals

The assessment in Section 4 indicates that the three design approaches generally provide overestimations of the bearing capacities of hot-rolled duplex stainless steel CHS axial compression members. In order to improve their accuracy, modified buckling curves developed based on the obtained test and FE data were proposed and are introduced in this section.

5.1 Modified buckling curves for EN 1993-1-4+A1 and CECS 410

Both of the flexural buckling expressions in CECS 410 and EN 1993-1-4+A1 adopt the Perry Robertson formula but with different imperfection factors and limiting slendernesses. Modification to these design equations is essentially the proposal of suitable imperfection factors and limiting slendernesses. Calibrated against the test and FE data, it is proposed to adopt $\alpha = 0.42$ and $\bar{\lambda}_0 = 0.26$ for the design of hot-rolled duplex stainless steel CHS columns.

The proposal (named as Proposal 1 herein) is compared with the test and FE results and the corresponding EN 1993-1-4+A1 and CECS 410 design curves in Fig. 14. In general, the proposed curves provide a closer fit to the test and FE data than the codified curves while maintaining the conservativeness. The normalised test and FE capacities $N_u / N_{u,\text{pred}}$ by the CECS 410 and EN 1993-1-4+A1 predictions varying with $\bar{\lambda}$ are given in Fig. 15, where the results normalised by the Proposal 1 predictions are also included for comparison purpose. It can be seen in Fig. 15 that the Proposal 1...
gives more uniform estimation of the test and FE results with reduced scatters for all the length domains than the codified methods. The numerical values of $N_u /N_{u,pred}$ plotted in Fig. 15 are also summarised in Table 6. The mean value of $N_u /N_{u,pro,1}$ equals to 1.04, which is superior to the corresponding CECS 410 predictions. The coefficients of variations (COV) of $N_u /N_{u,pro,1}$ equals to 0.03, which is superior to the corresponding CECS 410 and EN 1993-1-4+A1 predictions. Therefore, it can be concluded that the Proposal 1 can provide more satisfactory prediction to the resistance of such columns than those given in EN 1993-1-4+A1 and CECS 410.

**Fig. 14** Comparison of the CECS 410, EN 1993-1-4+A1 and Proposal 1 buckling curves with the test and FE data

**Fig. 15** Test and FE data normalised by the predictions made by the proposed design curve (Proposal 1), the CECS 410 and EN 1993-1-4+A1 design curve varying against the column slenderness
5.2 New flexural buckling curve proposals for AISC DG 27

The flexural buckling curve expression in AISC DG 27 (Eqs (6) and (7)) is defined as a two-stage curve and can be rewritten into the format of Eqs (8) and (9) where \( a_1 \) is the factor that defines the division of the two stages, \( a_2 \) is the factor that governs the buckling resistance in the inelastic range and \( a_3 \) is the reduction factor to the Euler resistance in the elastic range.

\[
F_{cr} = \begin{cases} 
F_y \left( \frac{F_e}{a_2} \right) & \text{for } \frac{KL}{r} \leq a_1 \sqrt{\frac{E}{F_y}} \\
F_e a_3 & \text{for } \frac{KL}{r} > a_1 \sqrt{\frac{E}{F_y}} 
\end{cases} \tag{8}
\]

\[
F_{cr} = a_3 F_e & \text{for } \frac{KL}{r} > a_1 \sqrt{\frac{E}{F_y}} \tag{9}
\]

It should be noted that this format of expression is also adopted in ANSI/AISC 360-10 [32] for the design of conventional steel structures, and AISC DG 27 retains the same format but adopts smaller values of \( a_1 \), \( a_2 \) and \( a_3 \) for the design of stainless steel members. In order to give a better prediction to the resistances of hot-rolled duplex stainless steel CHS columns, updated values of \( a_1 = 4.24 \), \( a_2 = 0.586 \) and \( a_3 = 0.69 \) were derived based on the test and FE data aiming at producing the closest yet safe fit to the dataset. This proposal is named as Proposal 2 herein.

![Fig. 16 Comparison of the AISC DG 27 and Proposal 2 buckling curves with the test and FE data](image-url)
As shown in Fig. 16, the Proposal 2 is compared with the test and FE results and the AISC DG 27 curve. The ratios of the test and FE results to the AISC DG 27 and Proposal 2 predictions varying with column slenderness are plotted and compared in Fig. 17, and the averaged value of $N_u/N_{u,\text{pro,2}}$ is reported in Table 6. It can be seen from both Fig. 17 and Table 6 that the Proposal 2 design curve reports $N_u/N_{u,\text{pro,2}}$ values that are much closer to unity with reduced scatters compared to the AISC DG 27 design curve, suggesting that the Proposal 2 is more suitable for the design of such columns than AISC DG 27. This conclusion has also been supported by the results from reliability analysis, as detailed in Section 6.

6. Reliability analysis

In accordance with the guidelines of EN1990-Annex D [33], reliability analysis was carried out to verify the validity of the design methods in the above three design standards and the proposed buckling curves (Proposals 1 and 2) for hot-rolled duplex stainless steel CHS columns. According to the recommendation of reference [34], in the reliability analysis, the material over-strength factor for hot-rolled duplex stainless steel used was 1.10, and the coefficients of variation of the yield strength
$V_f$ and geometry $V_{\text{geometry}}$ were respectively 0.03 and 0.05. The results of reliability analysis are summarized in Table 7, where $\gamma_{M1}$ is partial safety factor, $V_\delta$ is the estimator for the coefficient of variation of the error term, $b$ is the average ratio of the test/FE resistance to model resistance, and $k_{d,n}$ is the design fractile factor and is related to the number of test and FE results ($n$).

From Table 7, it can be seen that the EN 1993-1-4+A1 design curve report $\gamma_{M1}$ value that does not meet the target of $\gamma_{M1} \leq 1.1$ as set out in EN 1993-1-4+A1 [20], while CECS 410 and Proposal 1 design curves report $\gamma_{M1}$ values that meet the target of $\gamma_{M1} \leq 1.1$. Among these three curves, the Proposal 1 curve is able to achieve higher accuracy with reduced scatters in predicting the resistances of hot-rolled stainless steel CHS columns (Table 6) while satisfying the Eurocode reliability requirement. The required partial safety factor of AISC DG 27 ($\gamma_{M1} = 1.374$) fails significantly to meet the target value of $\gamma_{M1} \leq 1.1$. The Proposal 2 buckling curve developed in the framework of the AISC DG 27 curve reports $\gamma_{M1}$ value of 1.146 that is marginally beyond the target of 1.1, but it has significantly improved accuracy compared to the AISC DG 27 design curve, as can be reflected by the reduced scatters ($V_\delta = 0.084$) and $b$ value ($b = 1.05$) that is closer to unity. The relatively higher $\gamma_{M1}$ factors required by the AISC DG 27 and Proposal 2 design curves may attributed to their higher scatters in the resistance predictions (i.e. higher $V_\delta$ value).

<table>
<thead>
<tr>
<th>Design method</th>
<th>$n$</th>
<th>$k_{d,n}$</th>
<th>$b$</th>
<th>$V_\delta$</th>
<th>$\gamma_{M1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CECS 410</td>
<td>122</td>
<td>3.17</td>
<td>1.13</td>
<td>0.087</td>
<td>1.088</td>
</tr>
<tr>
<td>EN 1993-1-4+A1</td>
<td>122</td>
<td>3.17</td>
<td>1.00</td>
<td>0.052</td>
<td>1.148</td>
</tr>
<tr>
<td>AISC DG 27</td>
<td>122</td>
<td>3.17</td>
<td>1.11</td>
<td>0.170</td>
<td>1.374</td>
</tr>
<tr>
<td>Proposal 1</td>
<td>122</td>
<td>3.17</td>
<td>1.03</td>
<td>0.033</td>
<td>1.053</td>
</tr>
<tr>
<td>Proposal 2</td>
<td>122</td>
<td>3.17</td>
<td>1.05</td>
<td>0.084</td>
<td>1.146</td>
</tr>
</tbody>
</table>

7. Conclusions

A comprehensive experimental and numerical investigation focusing upon the flexural buckling
performance of hot-rolled duplex stainless steel CHS columns subjected to axial compression is presented herein. The obtained experimental and numerical results have been compared against the existing design methods in European standard, EN 1993-1-4+A1, Chinese standard, CECS 410, and North American design guidance, AISC DG 27. It was found that the design methods in CECS 410 and AISC DG 27 are conservative in predicting the resistances of hot-rolled duplex stainless steel CHS columns, while the design method in EN 1993-1-4 + A1 might be unsafe in predicting the resistances for low slenderness values.

Based on the assessment results of current design methods, new column buckling curves, adopting the format of the flexural buckling expressions in AISC DG 27 and EN 1993-1-4+A1, were proposed. The superiority of the proposed buckling curves over the current codified design methods has been confirmed through careful reliability analyses.

Acknowledgement

This work was supported by the Beijing Excellent Talent Training Support (Grant No. 2017000026833ZK26), and National Natural Science Foundation of China (Grant No. 51922001 and 51421005).

References


