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Siu-Lai Chan
Department of Civil and Environment Engineering, The Hong Kong Polytechnic University

Zhi-Xiang Yu
School of Civil Engineering, Southwest Jiaotong University

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Z.W. Zhu*, T. Qin, X.W. Chen
Preface

These proceedings contain the papers presented at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation—joined a few years later by the Hong Kong Institute of Steel Construction.

These proceedings bring together most recent findings in numerical, theoretical and experimental research, as well as its practical implementation in design practice in the areas of Assembled Structure, Bridge, Cold-formed Steel, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue, Fire, High-Strength Steel, Impact and Protection, Intelligent Construction, New Material, Seismic Resistance, Stability, Stainless Steel, Structure Systems, Testing & Monitoring. The papers presented in these proceedings come from a wide range of countries/regions and will be a great reference source.

Specially, the subject matter has been categorized under the broad heading of:

**Volume I:** Keynotes Lectures, Assembled Structure, Bridge, Cold-Formed, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue


Each of the papers was subjected to stringent review by a panel of experts in the respective area. This peer review began with an assessment of the submitted abstracts and following this, authors were invited to submit their full manuscripts. Each manuscript was then carefully reviewed by relevant experts, and their recommendations on accepting, rejecting or modifying the submissions were strictly adhered to, before inclusion in the conference proceedings.
STUDY OF INITIAL IMPERFECTION OF CONCRETE-FILLED CIRCULAR STEEL TUBE COLUMNS FOR DIRECT ANALYSIS (ICASS’2020)

Z.J. Zhang 1, J.L. Xing 1, Y.P. Liu 2,3* and G.C. Li 1

1 School of Civil Engineering, Shenyang Jianzhu University, Shenyang, China 110168
E-mails: zhangjiuandyx@163.com;

2 Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China 999077

3 NIDA Technology Company Limited, Hong Kong Science Park, Hong Kong, China
E-mail: yaopeng.liu@connect.polyu.hk (Corresponding author)

Abstract: The initial imperfection and residual stress play important roles in the buckling resistance of both structural system and structural members. The latest Standard for Design of Steel Structures (GB50017-2017) firstly introduces the direct analysis method for the stability design of steel structures in China. The equivalent initial imperfections for steel members have been well specified in this code. However, as an important part of modern structures, there is limited research on the initial imperfections of steel-concrete composite members in relevant regulations in China. Therefore, it is urgent to study the equivalent initial imperfections of steel-concrete members for direct analysis. This paper collects extensive experimental data on concrete-filled circular steel tube columns (CFCSTC) for calibration of finite element models using software ABAQUS. The key factors affecting CFCSTC’s behaviors such as section dimensions, grades of steel and concrete, and width-to-thickness ratios have been taken into account. A comparative analysis for the CFCSTC with and without initial imperfections will be presented. From this study, the equivalent initial imperfection for CFCSTCs will be proposed for practical direct analysis of steel-concrete composite structures to achieve a safer and economical design without use of conventional effective length method.

Keywords: Concrete-filled square steel tube column; Initial imperfection; Direct analysis method; Finite element analysis (FEA)

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1 INTRODUCTION

Concrete-filled steel tubular columns are widely used in high-rise building structures because of their high bearing capacity, good ductility, and superior seismic performance. (Han 2020) With the rapid development of China’s economic construction, the building structures are constantly breaking through in span and height, while the building shape has become more complex. At the same time, various high-strength and high-performance materials are continuously introduced. These factors make the slenderness ratios of the structures and structural elements larger with significant increase of second-order effects. Also, the load path becomes complex. Thus, the conventional linear analysis method cannot provide a good prediction on the structural responses. The effective length method based on linear analysis for stability design faces great challenges in practical engineering. The latest Standard for Design of Steel Structures (GB50017-2017) introduces the direct analysis method for the first time, and
makes corresponding provisions on the design of steel structures by the direct analysis method. The equivalent initial geometric imperfection of steel members lays a foundation for the overall analysis of steel structures. Not that as an important part of modern structures, the steel-concrete composite members are rarely mentioned in China’s relevant codes or regulations, resulting in engineers having no relevant code provisions to consult when designing steel-concrete composite structures. Therefore, it is necessary to carry out comprehensive research on CFSTCs from traditional design methods to experimental research considering various section sizes, loading conditions and materials.

In recent years, a large number of research studies on CFCSTC can be found in the literature (Han et al. 2008, Yang and Han 2012, Liu and Han 2006, Ding and Yu 2005, Xiao and Huang 2011). J. Lindner et al. (J. Lindner et al 2018) found that axial pressure members are more sensitive to initial imperfection; Wang L.P. et al. (Wang et al 2021) compared the differences between the empty steel tube and the concrete filled steel tube columns in the loading process, the influence of different parameters on the performance of the CFSTCs were obtained; On the basis of the experiment verification, Liu Jing et al. (Liu Jing et al 2015) explores the influence of local compression area ratio, steel ratio, strength of steel and concrete on ultimate capacity. There are few studies on the initial imperfection of CFSTC. For this reason, this paper takes axially compressed CFCSTC members (Joachim 2018) as the research object. In order to put forward the equivalent initial geometric imperfection of CFSTC suitable for Chinese standards, the test results from China, American and other countries on CFSTC are collected. This paper provides theoretical and design basis for the direct analysis method of CFCSTCs.

2 CONCRETE FILLED CIRCULAR STEEL TUBE COLUMN CONSIDERING IMPERFECTION

2.1 Initial geometric imperfection

In steel standards, the mode of initial imperfection in the component geometry can be defined as:

\[ \delta_0 = e_0 \sin \frac{\pi x}{l} \]

(1)

in which, \( x \) is the distance from the first end of the member; \( \delta_0 \) is the initial deformation at \( x \); \( e_0 \) is the initial bowing at the middle of the member; \( l \) is the member length. The equivalent geometric imperfection of the member (Du et al. 2019) is shown in Fig. 1.

![Figure 1: Equivalent geometric imperfection](image)

2.2 Residual stress of steel

Initial material imperfection generally refers to residual stresses that are widely existing in hot-rolled or welded steel members. Residual stress is mainly caused by processes such as rolling, welding and cold forming. Residual stresses are self-balancing stresses in the members, and the stress distribution patterns have a great correlation with the shape of the cross-section. As an initial mechanical imperfection, residual stress will cause early yield and cracks of the member, and is also one of the factors affecting the stability performance of the axially loaded members. Therefore, the influence of residual stresses also needs to be considered in the design
of CFSTCs.

2.3 Procedure of consideration of initial imperfections

Before performing geometrical and material nonlinear analysis, the initial imperfection should be taken into account by offsetting the nodal coordinates by following the buckling mode shape. The keywords "**imperfection, file = buckle" (the job name of the eigen buckling analysis), step = 1" command is required to introduce the initial deformation.

In the nonlinear analysis allowing for geometrical and material nonlinearity, the displacement control plus correction of the arc length method is adopted for incremental-iterative nonlinear solution.

2.4 Amplitude of initial imperfection for CFCSTC

According to GB50017 (2017), the initial member imperfections vary from L/400 to L/250 for steel members. There is no doubt that the ultimate bearing capacity of CFCSTC will be reduced if the initial imperfection is included. However, there is limited research on the determination of initial imperfections for steel-concrete composite members. Thus, this paper aims to study the amplitude of initial imperfection for CFCSTC members. As no initial imperfections were reported in the literature, three equivalent initial geometric imperfections are assumed to study the sensitivity of amplitudes on the ultimate bearing capacity of the CFSSSTCs, as listed in Table 1. To clearly demonstrate the contribution of initial imperfection, a model “0” without imperfection is also presented.

<table>
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<th>Model</th>
<th>Initial Bowing Imperfection, e₀</th>
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<tbody>
<tr>
<td>0</td>
<td>0 (No imperfection)</td>
</tr>
<tr>
<td>1</td>
<td>3L/1000</td>
</tr>
<tr>
<td>2</td>
<td>L/1000</td>
</tr>
<tr>
<td>3</td>
<td>L/3000</td>
</tr>
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</table>

Because previous studies have found that initial imperfections have a greater impact on the bearing capacity at L/1000 to 3L/1000, they are not described in detail here. Totally five equivalent initial imperfections as listed in Table 2 are investigated.

<table>
<thead>
<tr>
<th>Model</th>
<th>Initial Bowing Imperfection, e₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>L/900</td>
</tr>
<tr>
<td>5</td>
<td>L/800</td>
</tr>
<tr>
<td>6</td>
<td>L/700</td>
</tr>
<tr>
<td>7</td>
<td>L/600</td>
</tr>
<tr>
<td>8</td>
<td>L/500</td>
</tr>
</tbody>
</table>

3 EXPERIMENTAL TEST DATA

In order to study the influence of initial imperfection on CFSSSTC, this paper collects nearly 100 sets of test data from literature. The data sources and the specimens adopted in this study are listed in Table 3. According to the section sizes and boundary conditions of CFCSTC in literatures, the finite element models are established in ABAQUS.

<table>
<thead>
<tr>
<th>Source of Experimental Tests</th>
<th>Specimen No.</th>
<th>D(mm)</th>
<th>t(mm)</th>
<th>L(mm)</th>
<th>f_c'</th>
<th>f_y</th>
<th>N_FE</th>
<th>N_E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hayashi (1990)</td>
<td>L-20</td>
<td>177.8</td>
<td>9.00</td>
<td>360</td>
<td>22.06</td>
<td>283.3</td>
<td>2015</td>
<td>1901</td>
</tr>
</tbody>
</table>
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3.1 Analysis of calculation results

17 groups of test results of concrete-filled circular steel tubular short columns in the literature are selected for finite element analysis. The model is established by the finite element theory in Section 4. The finite element results \( N_{FE} \) and test results \( N_E \) are shown in Table 3. The average value of the ratio between the test results and the finite element results is 1.001, and the dispersion coefficient is 0.070. It can be seen that the finite element calculation results are in good agreement with the test results.

The authors have studied that the simulation results of the column meet the specification requirements when considering the amplitude of equivalent initial imperfection \((e_0)\) is L/500.

4 FINITE ELEMENT MODEL

4.1 Establishment of model and constitutive relation

The finite element model of the CFCSTC column subjected to axial compression is established in ABAQUS. All the components of the column are modeled by solid element C3D8R. The steel tube-concrete interface adopts friction contact and hard contact with a friction coefficient of 0.6. The end plate-concrete adopts hard contact, while the end plate and steel pipe are connected by tie elements. The boundary conditions and applied load are shown in Fig. 2. When considering the constitutive relationship, in order to make the calculation results more credible, two constitutive relations are used, namely the constitutive relationship model proposed by Han L.H. and the constitutive relationship model proposed by the specification. The stress-strain relationship of low-carbon steel such as Q235, Q345 and Q390 can generally be divided into five stages (Han 2016), which is expressed in Eq. (2)(3); The constitutive relationship model of concrete adopts the model of longitudinal stress \((\sigma)\)-strain \((\varepsilon)\) of core concrete proposed by Han (2016), which is expressed in Eq. (4)(5).
\[ \sigma_s = \begin{cases} E_s \varepsilon_s & \varepsilon_s \leq \varepsilon_e \\ -A\varepsilon_s^2 + B\varepsilon_s + C & \varepsilon_e < \varepsilon_s < \varepsilon_{e1} \\ f_y (1 + 0.6 \frac{\varepsilon_s - \varepsilon_{e2}}{\varepsilon_{e3} - \varepsilon_{e2}}) & \varepsilon_{e2} < \varepsilon_s < \varepsilon_{e3} \\ 1.6f_y & \varepsilon_s > \varepsilon_{e3} \end{cases} \] 

(2)

with

\[ \begin{align*}
\varepsilon_e &= 0.8f_y/E_s \\
\varepsilon_{e1} &= 1.5\varepsilon_e \\
\varepsilon_{e2} &= 10\varepsilon_{e1} \\
\varepsilon_{e3} &= 100\varepsilon_{e1} \\
A &= 0.2f_y/(\varepsilon_{e1} - \varepsilon_e)^2 \\
B &= 2A\varepsilon_{e1} \\
C &= 0.8f_y + A\varepsilon_{e1}^2 - B\varepsilon_e \\
y &= \begin{cases} 2x - x^2 & (x \leq 1) \\ x & (x > 1) \end{cases}
\end{align*} \] 

(3)

4.2 Model Validation

In order to verify the validity of the model, it was necessary to compare the load-strain curves obtained from the ABAQUS finite element calculations with the experimental studies. The results showed that the numerical simulation results agreed well with the experimental results. However, it could be found that the initial stiffness of the curve was less than the numerical simulation results, possibly due to the presence of initial imperfection in the specimen, which
led to the rapid development of lateral deflection during the stressing process. For this reason it proves that initial imperfection need to be considered.

4.3 Parametric analysis

Based on the above analysis, 13 finite element models for CFCSTC 1 under axial load are established. The main parameters are concrete compressive strength (i.e. $f_{cu}$ from 30Mpa to 50Mpa), steel yield strength (i.e. $f_y$ from 235Mpa to 420Mpa) and the length of the component (i.e. $l$ from 1000mm to 2000mm). The settings for boundary conditions and applied load of the finite element model are shown in Fig.2. The specific parameters and the numerical results are shown in Table 4.

<table>
<thead>
<tr>
<th>Model</th>
<th>$D \times t \times L$</th>
<th>$f_{cu}$</th>
<th>$f_y$</th>
<th>$D/t$</th>
<th>$P_u$</th>
<th>$P_{ue}(e_0=L/500)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFCSTC-1</td>
<td>100 × 5 × 1000</td>
<td>30</td>
<td>345</td>
<td>20</td>
<td>622.0</td>
<td>478.0</td>
</tr>
<tr>
<td>CFCSTC-2</td>
<td>100 × 5 × 1000</td>
<td>30</td>
<td>390</td>
<td>20</td>
<td>676.3</td>
<td>555.1</td>
</tr>
<tr>
<td>CFCSTC-3</td>
<td>100 × 5 × 1000</td>
<td>30</td>
<td>420</td>
<td>20</td>
<td>716.0</td>
<td>637.0</td>
</tr>
<tr>
<td>CFCSTC-4</td>
<td>100 × 5 × 1000</td>
<td>40</td>
<td>345</td>
<td>20</td>
<td>645.6</td>
<td>516.0</td>
</tr>
<tr>
<td>CFCSTC-5</td>
<td>100 × 5 × 1000</td>
<td>40</td>
<td>390</td>
<td>20</td>
<td>694.0</td>
<td>582.9</td>
</tr>
<tr>
<td>CFCSTC-6</td>
<td>100 × 5 × 1000</td>
<td>40</td>
<td>420</td>
<td>20</td>
<td>728.5</td>
<td>688.0</td>
</tr>
<tr>
<td>CFCSTC-7</td>
<td>100 × 5 × 1000</td>
<td>50</td>
<td>345</td>
<td>20</td>
<td>672.4</td>
<td>558.0</td>
</tr>
<tr>
<td>CFCSTC-8</td>
<td>100 × 5 × 1000</td>
<td>50</td>
<td>390</td>
<td>20</td>
<td>717.6</td>
<td>609.8</td>
</tr>
<tr>
<td>CFCSTC-9</td>
<td>100 × 5 × 1000</td>
<td>50</td>
<td>420</td>
<td>20</td>
<td>749.5</td>
<td>674.5</td>
</tr>
<tr>
<td>CFCSTC-10</td>
<td>100 × 5 × 1500</td>
<td>40</td>
<td>345</td>
<td>20</td>
<td>645.6</td>
<td>464.8</td>
</tr>
<tr>
<td>CFCSTC-11</td>
<td>100 × 5 × 2000</td>
<td>40</td>
<td>345</td>
<td>20</td>
<td>609.0</td>
<td>383.7</td>
</tr>
<tr>
<td>CFCSTC-12</td>
<td>100 × 4 × 1000</td>
<td>40</td>
<td>345</td>
<td>25</td>
<td>580.1</td>
<td>452.5</td>
</tr>
<tr>
<td>CFCSTC-13</td>
<td>100 × 6 × 1000</td>
<td>40</td>
<td>345</td>
<td>25</td>
<td>689.2</td>
<td>606.5</td>
</tr>
</tbody>
</table>

Note: $P_u$ is the ultimate bearing capacity from finite element analysis, while $P_{ue}$ is obtained from the proposed finite element model with different amplitude of initial imperfection.

4.3.1 Influence of concrete strength

Figure 3 (a)(b) show the P-Δ curve under the influence of concrete strength ($f_{cu}$) and initial imperfection. When the amplitude $e_0$ is L/500, the concrete strength is increased from 30Mpa to 50Mpa (increased 66.7%), the reduction in the bearing capacity of the column is reduced from 23% by 17%. It shows that with the strength of the concrete increases, the impact of initial imperfection on the column decreases.

4.3.2 Influence of steel yield strength

Figure 4 (c)(d) show the P-Δ curve under the influence of steel strength and initial imperfection. In the case of amplitude $e_0$ is L/500, when the yield strength of the steel is increased from 345Mpa to 420Mpa (increased 21.7%), the bearing capacity of the column is reduced from 23% to 11%. It can be seen that when considering the initial imperfection, the influence of steel strength on the bearing capacity of the column is more obvious.

4.3.3 Influence of slenderness ratio

Figure 5 (e)(f) show the P-Δ curve under the influence of the slenderness ratio ($\lambda$) and initial imperfection. It can be seen that with the increase of the slenderness ratio, the lateral deflection of the component develops rapidly. Due to the difference in initial imperfection, when the slenderness ratio is increased from 40 to 80, the bearing capacity of the column is also reduced by different amounts, from the original 20% to 35%. It can be seen that the slenderness ratio of the column is changed, and the bearing capacity changes greatly.
4.3.4 Influence of steel ratio

Figure 6 (g) (h) show the P-Δ curve under the influence of initial imperfection and steel ratio (α). The increase of α increases the elastic stiffness of P-Δ curve. When the α increases from 0.181 to 0.291, the reduction of bearing capacity decreases from 22% to 12%. It can be seen that the influence of the α on the bearing capacity is similar to that of the above-mentioned steel yield strength. Compared with the amplitude $e_0$ is L/600, the influence of the α on the bearing capacity of the amplitude $e_0$ is L/500 is more obvious. Because steel is a plastic material, increasing the yield strength or the α is conducive to improving the bearing capacity of members with large slenderness ratio.

Figure 3: Influence of concrete strength

Figure 4: Influence of steel yield strength
Figure 5: Influence of slenderness ratio

Figure 6: Influence of steel ratio

5 CONCLUSIONS

In this paper, the equivalent initial geometric imperfection of CFCSTCs for direct analysis are studied by using finite element analysis against the experimental test data. The following conclusions can be drawn from the scope of the study in this paper:

(1) ABAQUS numerical simulation results show that the influence of initial imperfection on bearing capacity increases with the increase of slenderness ratio of columns; Increasing concrete strength, steel strength and steel ratio can improve the bearing capacity of the column, and the effect of steel yield strength on the bearing capacity is more obvious.

(2) Results of the numerical models using ABAQUS compared with the results of specification, thus, it is proved that the bearing capacity of the CFCSTCs meets the requirements of the specification. The finite element model with the proposed equivalent initial imperfection also meets the requirements of the specification.

(3) It is recommended that the equivalent initial geometric imperfection of CFCSTCs in the direct analysis of practical projects should be not less than L/500.
REFERENCES


These proceedings contain the papers at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation - joined a few years later by the Hong Kong Institute of Steel Construction.

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